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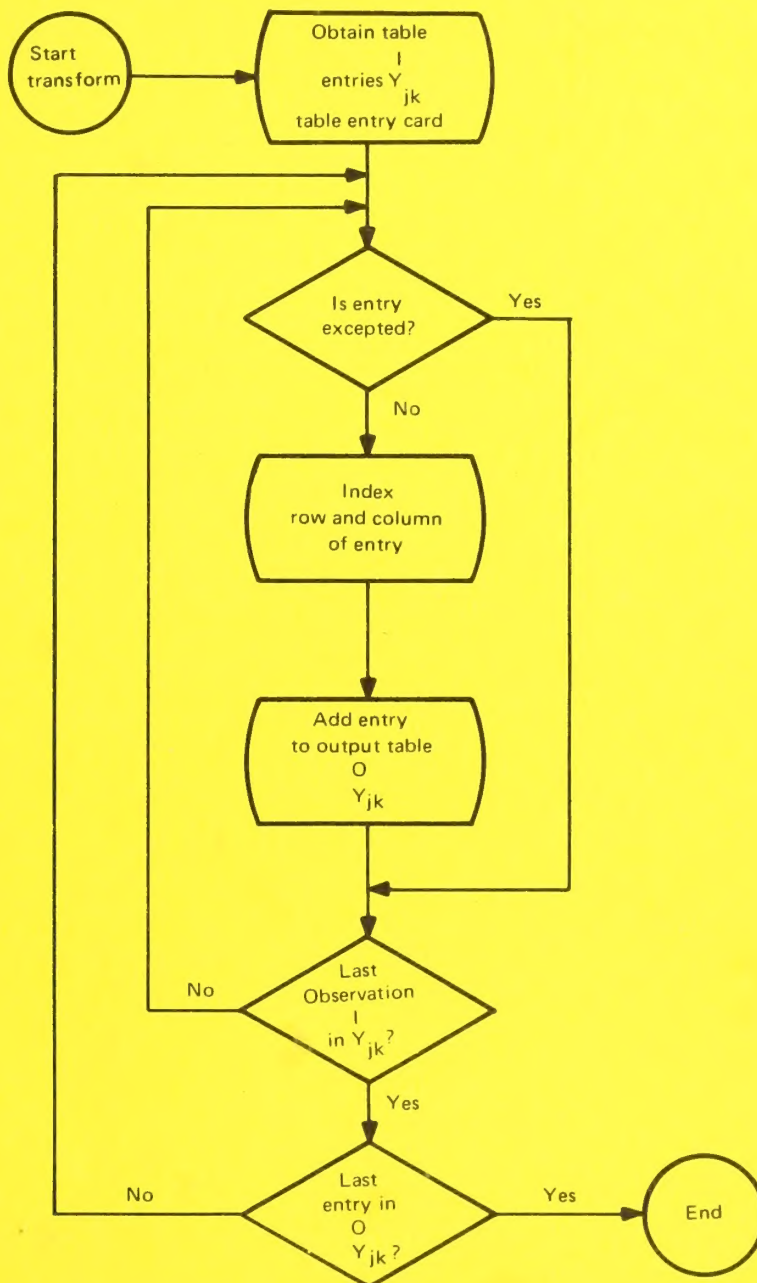
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FINSYS-2: Subsystem TABLE-2 and OUTPUT-2

J. David Born

Joseph E. Barnard



ABSTRACT

Describes a computer software package for use in developing statistical tables from a resource inventory data set. The flexibility of the system in performing user-designated table-making functions also is described. Full instructions for operating the system are included.

THE AUTHORS

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PREFACE

Since the original version of FINSYS was published in 1967, many people have modified and added to the system programs and documentation to make the general system more flexible and easier to use. This major revision includes an accumulation of changes that make the general system more usable to a broad spectrum of users.

The initial revision of the system programs was made by Dr. Warren E. Frayer, Colorado State University, in cooperation with the Forest Service. He was guided by a committee of Forest Service specialists including the authors; David A. Neebe, Washington Office; and John Berger, Pacific Northwest Forest and Range Experiment Station.

The Renewable Resources Evaluation unit at the Intermountain Forest and Range Experiment Station further modified the systems programs and documentation. Major contributions were made by the following members of the Intermountain Station staff:

Gary L. Carroll, text revisions; Terrence S. Throssell, Gary W. Clendenen and James C. Schaefer, program and text revisions; Shirley H. Waters, Donald L. Johnson, and Jack W. Homeyer, program revisions.

The FINSYS-2 programs may be requested from either of the two addresses below. The preferred method of distributing program files is by a user-supplied computer tape. Requests should specify the computer to be used and program file specifications.

Forest Inventory and Analysis, Northeastern Forest Experiment Station, 370 Reed Road, Broomall, Pennsylvania 19008; phone (215)461-3037.

or

Forest Inventory and Analysis, Intermountain Forest and Range Experiment Station, 507 25th Street, Ogden, Utah 84401; phone (801)625-5377.

Further information concerning the use of FINSYS-2 for specific applications or sampling designs can be obtained by contacting the authors.

The computer program described in this publication is available on request with the understanding that the U.S. Department of Agriculture cannot assure its accuracy, completeness, reliability, or suitability for any other purpose than that reported. The recipient may not assert any proprietary rights thereto nor represent it to anyone as other than a Government-produced computer program. For cost information, please write: Forest Inventory and Analysis, Northeastern Forest Experiment Station, 370 Reed Road, Broomall, PA 19008.

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I. INTRODUCTION

This is a description of operating instructions and basic information for users of FINSYS-2 Subsystems TABLE-2 and OUTPUT-2. This publication is a revision of "The Northeastern Forest-Inventory Data Processing System"--(Wilson and Peters 1967 a, b, c, d, e, f).

One of the major projects of the Forest Service is a nationwide forest survey, which is designed to obtain useful and timely information about the timber resources of the United States. In the course of the surveys, which are made mainly on a state-by-state basis, great masses of detailed data are collected about timber volumes, growth, timber cut, and other characteristics of the timber resource.

Over the years, the volume of information obtained from forest survey work has increased greatly. The task of compiling and analyzing this mass of data with mechanical computing machines was both cumbersome and time-consuming.

With the advent of high-speed electronic computers, the Northeastern Forest Experiment Station devised the Northeastern Forest-Inventory Data-Processing System (FINSYS). Although this revision of the original FINSYS system accomplishes the same purposes as the original, the user can handle a greater variety of data-processing options with less effort. The revised system, FINSYS-2, is not compatible with the earlier version, so present users of the system must alter their processing controls to use the new version. However, the data handling concepts are similar and the benefits gained may well be worthwhile.

TABLE-2 and OUTPUT-2 are the part of the FINSYS-2 system that is designed specifically to reduce large amounts of sample data to tables of statistics. TABLE-2 produces sample summary output which is designed for use as input to OUTPUT-2 to produce tables of statistics for the sampled populations. EDIT-2 which edits data with some computational capability is described in Barnard and Born (1978).

Each of the FINSYS-2 Subsystems is composed of a single large computer program, with a number of subroutines. These programs are controlled by a number of specified processing options.

The programs are written in the standard FORTRAN IV language, and are operative on UNIVAC, CDC, IBM, Honeywell, and other computers throughout the United States. They will operate with little or no modification on comparable systems.

Also available for use with TABLE-2 is PARMS (Throssell 1979), a program which automatically modifies the dimensioned space according to the requirements of the user. The PARMS program is not required to use TABLE-2, but it provides efficient and automatic allocation of storage when job requirements vary with users of the same computer or data sets. PARMS is available for UNIVAC, CDC, and IBM systems, and it could be modified for use with other large computer systems.

This report includes programing information that will be useful if the programs must be modified for any reason. Detailed instructions for setting up and executing jobs are also given.

The principal value of the programs lies in their versatility. While applying a standard, straightforward procedure to the reduction of data, they provide a large amount of freedom in fitting both inputs and outputs to the requirements of particular data-reduction problems. Within the context of the programs, the origin of the input data is immaterial; a data set that is to be processed may be sample data, but it need not be. The data set is simply a collection of values for one or more attributes of one or more objects (sampling units) that are to be reduced to tables of statistics that characterize the set. A data set might be a complete set of samples, a sampling stratum, or a single sample. Similarly, the output tables may summarize any elements of data from the data set. Several different tables, each representing all or a selected part of the input data, may be used to form these summaries. And, in order that both the inputs and the outputs may be variable, the details of the procedures by which one is converted to the other are also variable. Consequently, the programs can be applied to a wide variety of data-reduction problems.

A. TABLE-2 OUTPUTS

The primary outputs from TABLE-2 are sets of statistical tables. One set of output tables is produced for each set of sample input data. An output set may consist of up to 40 (153 optional) two-dimensional tables. No table in the set may have more than 201 rows and 101 columns, including the row and column subtotals and totals that are formed for every table.

The content of the tables in an output set depends entirely upon the demands of the particular application. Any attribute of the sampling units in a data set can be summarized by categories determined from other sampling-unit attributes.

In addition there is a choice of statistics representing sampling options, to be provided for every cell of each table in output data set. The choices are:

1. Simple sums over sampling units.
2. Means over sampling units.
3. Means and their variances over sampling units.
4. Means, their variances, and their covariances with the grand mean over the sampling units (for use when the data set summaries are to be used to make ratio estimates).
5. Means and their variances over sampling units, with unequal probabilities of selection for sampling units. (Options 1-4 assume equal probabilities of selection for sampling units within a data set.) This option also allows the sampling unit to be divided into more than one data set within a population.

All output sets from a program run are written on a single file of binary records for rapid transmission to OUTPUT-2, in which the tables are labeled and printed as population statistics after appropriate weighting and summing. The relationship between the output options in TABLE-2 and the ones used in OUTPUT-2 is discussed in the section on data inputs for OUTPUT-2. For the purpose of debugging the Job Control Deck, the alternative of printing the tables in block form as BCD records is also available. A binary file can be written with this option, if desired.

During execution, the program prints a job summary consisting of messages of three types: those that identify errors in the Job Control Deck that have halted execution, those identifying errors in input records (or the Job Control Deck) that cause the record to be deleted but processing to continue, and those that signal successful reading of the Job Control Deck and identify the data sets and numbers of sampling units that have been processed.

B. TABLE-2 DATA INPUTS

The data input to the program consists of a single file of ordered unit records. Each record in the file must have exactly the same format as every other record. The file contains the data from sets of observed sampling units. How the sampling units are represented by the unit records depends upon the characteristics of the particular problem. The key is the way in which the field observations were made.

If all attributes were actually observed on the sampling unit as a whole (a plot, for example), the sampling unit observation would consist of a single value for each attribute. The sampling unit observation could then be represented by a single unit record.

If, however, all attributes were observed on subdivisions of the sampling unit (on trees in the plot, for example), then there would be several values for each attribute. In this case, one unit record would be required to represent each observed value of the set of attributes, so the sampling unit as a whole would be represented by a set of unit records equal in number to the number of subdivisions on which observations were made.

Generally, attributes of both kinds are observed on sampling units. In this case, there must still be a unit record to represent each subdivision observed, but the unit record format must also provide for entry of the single-valued attributes observed on the sampling unit as a whole. These values are repeated in every unit record of the set representing the sampling unit.

An additional possibility arises if attributes are actually observed on the sampling unit as a whole, on subunits of the sampling unit, and on subdivisions of the subunits. This is simply an extension of the previous case. The unit record format must provide for recording the values of all three kinds of attributes. There will be one unit record representing each observed subdivision of the subunits. The values of attributes observed on the subunits will be repeated in each record of the subset representing the subunit; and, as before, the values of attributes observed on the sampling unit as a whole will be repeated in each record of the whole set representing the sampling unit.

In summary, then, the individual unit record always represents the smallest subdivision of a sampling unit that has been directly observed, whatever that may be. The maximum allowable number of unit records in the sets representing sampling unit sets is specified on a control card. The unit records must have a common format, and appropriate values for each of up to three kinds of attributes actually observed on a sampling unit must be recorded in every unit record. There is no provision for header cards of any kind.

The order of the unit records in the input file also depends on the characteristics of the problem. The unit records must always be ordered by subunits, if any, within sampling units. In turn, the sampling unit sets must always be ordered into data sets. The significance of the data set is that it contains all the data required to make one set of output tables. What the data set represents in terms of the population that has been sampled depends upon the methods of sampling and of compilation that are employed. In stratified sampling, it will represent a sampling stratum. In other types of sampling, it will generally represent any kind of geographical or other unit for which output tables of statistics are required. Any number of data sets may be contained in the input file.

If required by the problem, the data sets themselves may be ordered into groups; and these groups, in turn, into still larger groups. For example, if stratified sampling has been employed in each of several geographical areas covering the population sampled, then the data sets must be ordered by geographical area. However, it must be remembered that all data sets processed in a single production run are subject to the same set of processing rules.

C. TABLE-2 LOGIC AND PROCEDURES

The program consists of seven principal phases or steps connected in a simple and straightforward manner (fig. 1). The first step simply reads and stores in the computer all of the control information contained in the Job Control Deck.

The second step reads a set of unit records representing a sampling unit and stores all of the data in blocks, according to the kind of attributes represented in each data field. Consequently, all input data for a sampling unit are available throughout the processing of that sampling unit.

The third step executes the CALCUL subroutine. This step is provided to allow the calculation of data field values from information in more than one unit record of the sampling unit set, since this kind of operation cannot be performed in a unit record editing process.

The fourth step produces the facsimile output tables at the sampling unit level. This key step in the compilation process is discussed in detail later.

The fifth step adds the completed sampling unit tables to the output tables being accumulated for the data set; and if required, also adds tables of squares and of cross-products (of cells with totals) to special data set tables used to compute variances and covariances.

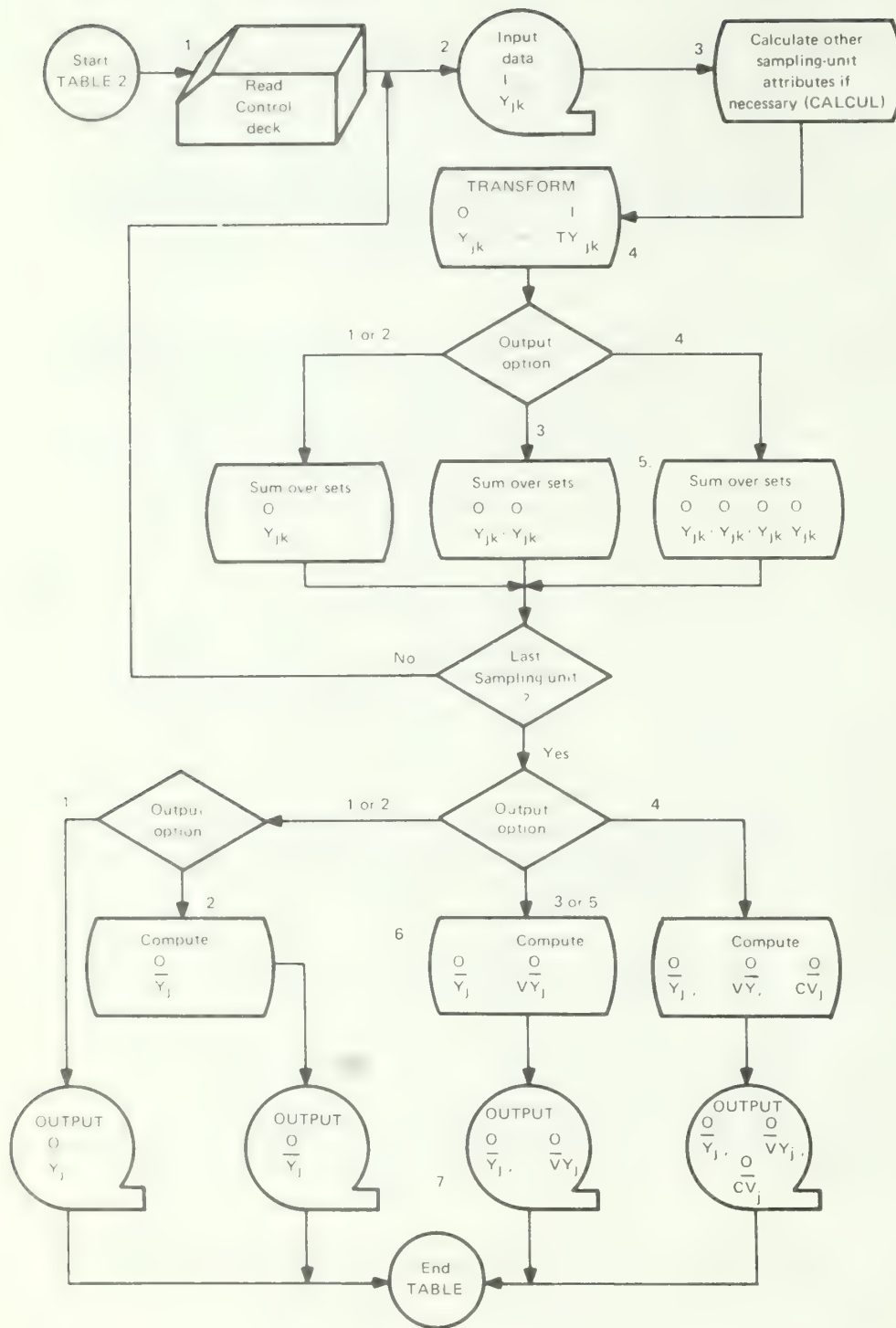


Figure 1.--A generalized flow chart of TABLE-2

Steps two to five are repeated until every sampling unit in the data set has been processed. Then, the sixth step computes the required statistics for each output table from the sums that have been accumulated. The tabulated statistics are written on a file in binary mode (or printed, if the debugging output option has been taken) in the seventh and final step.

If there are additional data sets to be processed, the program then returns to step two and the cycle is repeated for each successive set.

The formation of final output tables begins with the formation of facsimile output tables for each input sampling unit, in sequence. The formation of these tables is governed entirely by a general table-making procedure provided in the program in conjunction with information about the relationships between sampling unit data and output tables in a given application that is conveyed to the program in the Job Control Deck.¹

¹The process of forming the facsimile output tables for the sampling units is similar in concept to a matrix transformation:

$$\begin{matrix} O & I \\ Y = T & Y \end{matrix}$$

where O_Y = a given two-dimensional facsimile output table in which an input attribute is tabulated according to the values of two other attributes;

T = the transform that controls the process, consisting of the general table-making procedure and the control information for a given job;

and

I_Y = a two-dimensional array of sampling unit input in which the data are tabulated according to observation (rows) and attribute (columns).

The general procedure (fig. 2) provides that each observed value of a given attribute² is summed (entered) into a given facsimile table in a particular row and column (table cell), unless conditions are specified under which certain values of the attribute are not to be entered. The procedure also provides that up to 10 attributes may be entered in a given table. The general procedure can form almost any kind of tabulation of sampling unit data.

The information provided in the TABLE-2 Job Control Deck defines the particular set of tables required. For each table, the following information is given:

1. A short, unique name by which the table can be identified.
2. The dimensions (number of rows and number of columns including subtotals but excluding row and column totals) of the table.
3. The attributes in the sampling unit data that are to be summed into the table. The values of these attributes must be expressed as real or floating-point numbers (F format).
4. The attributes in the sampling unit data that determine the row and the column (table cell) in the table into which each value of the entry attribute is to be summed. The values of these attributes must be expressed as integer or fixed-point numbers (I format).
5. The operations (and input tables, if any) by which values of the index attributes are converted to row and column indexes are chosen from among the five operations that are available in the program:

²The number of entries of a given attribute per sampling unit depends upon the kind of attribute and the number of subdivisions of the sampling unit on which it was observed. If the attribute was observed on the sampling unit as a whole, it has only one value, so only one entry is made in the appropriate facsimile tables. If the attribute was observed on a subdivision of a sampling unit, there will be as many values (and as many entries in the table) as there were subdivisions of the sampling unit. The general procedure automatically enters each observed value of an attribute, using information about the attribute classification furnished with the input record description in the Job Control Deck.

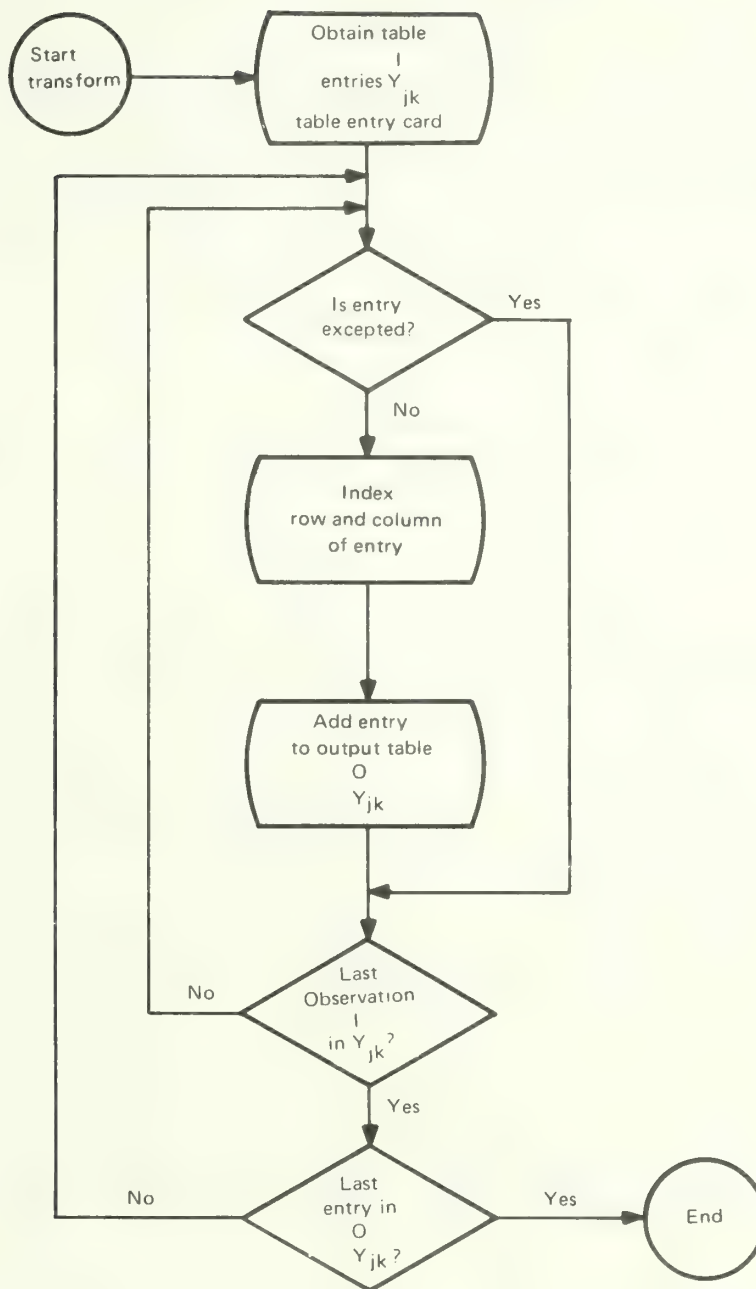


Figure 2.--Flow chart of transform operations in TABLE-2

(a) LIST, the operation that defines an index as the position in a list occupied by a given value of an index attribute. An input table contains the list of all values the given attribute is allowed to assume. For example, assume the following relationships between the values of an attribute and the rows of an output table into which an entry is to be made: when the value is 1, the entry is in the second row; when the value is 2, the entry is in the third row; when the value is 4, the entry is in the fourth row; and when the value is 6, the entry is in the first row. Because there are four possible values of the index attribute in one-to-one correspondence with a row index, there must be four entries in the input table: 0006, 0001, 0002, and 0004. "Dummy" values must be included in the list if subtotals are to be produced with the LIST operation to allow for the position of each subtotal in the list.

(b) RANGE, the operation that defines an index position in a list occupied by a range of values that contains a given value of an attribute. An input table contains the list of ranges that cover all possible values for the given attribute. As with the LIST operation, space must be included in the input table if subtotals are used.

For example, assume the following relationships between the values of an attribute and the columns of an output table into which an entry is to be made: when the value of the index attribute is less than 50, the entry is to be made in column 1; when the value is between 50 and 73, inclusive, the entry is to be made in column 2; and when the value is between 74 and 99, inclusive, the entry is in the third column. There must be three entries in the input table: 00000049, 00500073, and 00740099. "Dummy" ranges must be included in the table if subtotals are to be produced with the RANGE operation.

(c) LOOKUP, the operation that defines an index as the value in one list of values whose position corresponds to the position in another list occupied by a given value of an attribute. An input table provides both lists. For example, assume the following relationships between the values of a given attribute and the rows of an output table into which an entry is to be made: when the value is 1 or 7, the entry is in the first row; when the value is 2, 3, or 4, the entry is in the second row; and, when the value is 5 or 6, the entry is in the third row. Since seven values of the attribute are allowed there must be seven entries in the input table:

00010001, 00020002, 00030002, 00040002, 00050003, 00060003, and 00070001. The row or column for a subtotal must not be specified in the LOOKUP input table.

(d) EQUATE, the operation that defines an index as equal to a given value of an attribute. No input table is required. The row or column for a subtotal must not be a value of the attribute for an EQUATE operation.

(e) CONST, the operation that defines an index as equal to a given constant. No input table is required but the constant must be specified along with the operation name. The row or column for a subtotal must not be specified by the CONST operation.

6. The conditions under which a value of an entry attribute is not to be summed into a given facsimile output table are referred to as exceptions. Each condition requires the specification of an attribute, a constant, and a relation operator. The exception (no entry) is whenever a value of the attribute bears the specified relation to the constant. Up to 10 conditions may be applied to any entry attribute providing that the total number specified in the Job Control Deck does not exceed 100.

D. OUTPUT-2 OUTPUTS

The primary outputs from OUTPUT-2 are printed tables of statistics for sampled populations, selected from among the tabular summaries produced for the data sets (samples) in TABLE-2.

The basic statistics put out for each selected table are cell-by-cell sums (including row and column subtotals and totals) of the sampling unit attributes contained in the table over all sampling units in the population. The corresponding variances of these sums (except that the zero variances for populations wholly contained in the samples are not printed) is an option provided by the program. In addition, tables of the corresponding standard errors of estimate, expressed either in absolute terms or as percentages, may be obtained on an optional basis.

Each statistic for each of the selected output tables is printed in the format specified for that table in the TABLE-2 Job Control Deck. A maximum of 51 rows and 5 columns are printed per page, complete with table title, row and column headings (as supplied in the OUTPUT-2 Job Control Deck), and the name of the statistic. Larger tables are printed on multiple pages, each page being fully labeled.

Outputs equivalent to those just described can also be obtained on an optional basis for groups of populations. These statistics are simple sums of the individual population statistics.

In addition to, or in place of, these primary outputs, other modified outputs of the same general format can be obtained. For example, tables of population totals and their variances can be replaced by tables of means and their variances. Under certain conditions, the tables of population statistics can be replaced by tables of sample statistics; or, under an appropriate assumption of homogeneity within the population, by tables of statistics for particular segments of the population. However, modifications of this kind require judicious choice of a successful combination of input data, weights, expansion factors, and processing options. They should not be undertaken without a thorough understanding of the sampling method, the estimating problem, and the program logic and procedures.

E. OUTPUT-2 DATA INPUTS

The data input to OUTPUT-2 must be a single file of binary records that contains the data set (sample) summaries for all populations that are to be processed in a given run. It may also contain summaries of data sets that are not to be processed in the run. These will simply be passed over during processing. A set of tables produced on punched cards during a previous run may also be included as data input under an update option. Entries in these tables will be added to the results produced during the current run.

The file produced for these samples in TABLE-2 is the appropriate input to OUTPUT-2, provided that care has been taken to reconcile the output option of TABLE-2 with the processing option of OUTPUT-2. It is also necessary that the data set summaries applicable to a given population appear one after the other and in known order in the input file. Consequently, the same order should appear in the input file to TABLE-2.

F. OUTPUT-2 LOGIC AND PROCEDURES

The underlying logic and procedures of OUTPUT-2 are quite simple (fig. 3). The first step always is to read the Job Control Deck into the computer, interpret the specifications it contains, and store the necessary information. The interpretation includes the setting up of the processing option (see below) and the output options specified in the Job Control Deck. The Job Control Deck also contains the labels to be printed with the output tables, and all weights and expansion factors required in processing the job. In the general case, this setup phase is followed by several distinct phases in which the actual processing is accomplished.

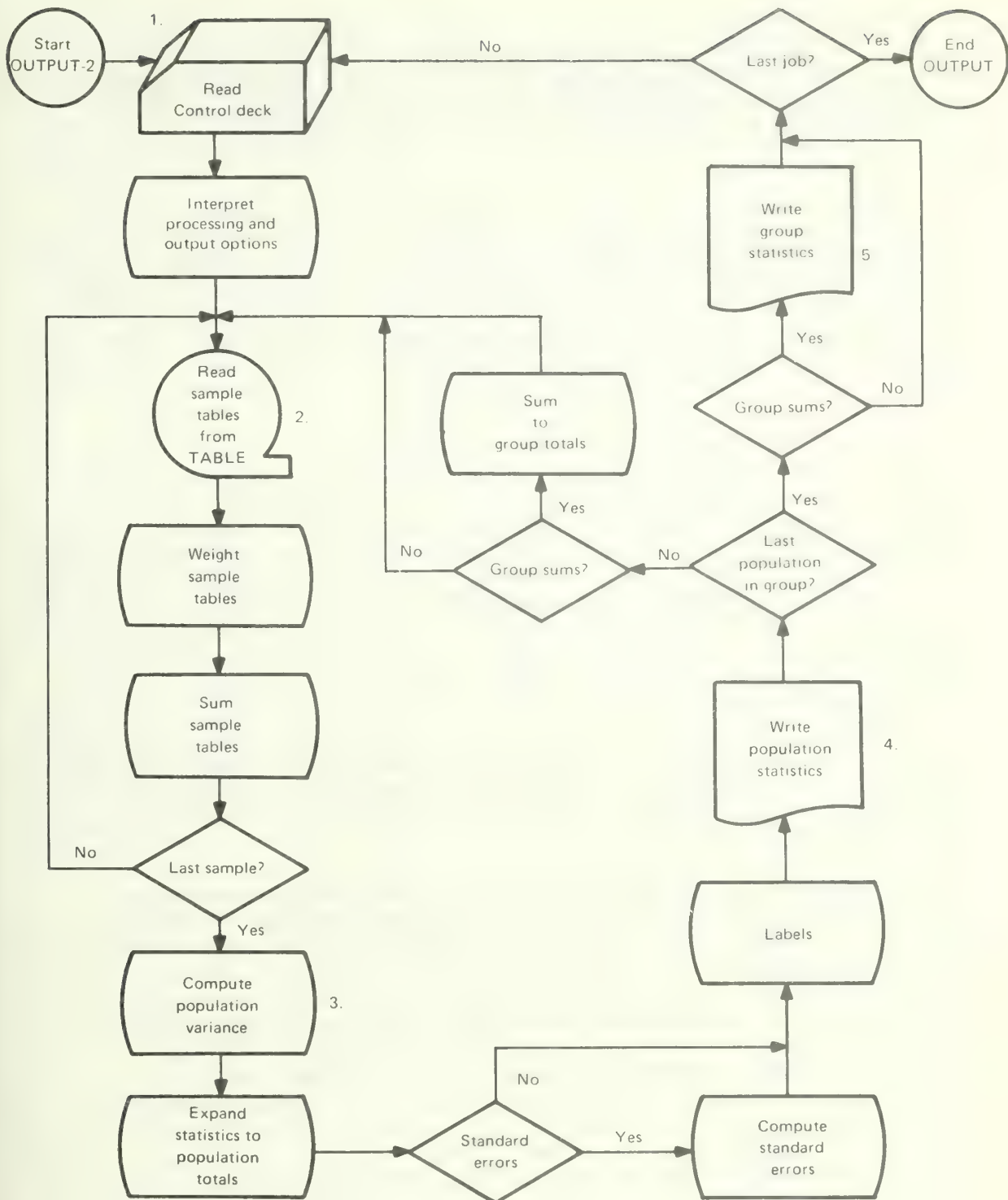


Figure 3.--A generalized flow chart of OUTPUT-2

First, the entire set of tabular summary data for a data set (stratum) from a given population is read into the computer; and the selected tables are weighted and summed to population totals. This phase is repeated until all samples from the population have been processed.

Second, the final population variances are computed and, if elected, so are the standard errors of estimate. After all statistics are multiplied by the appropriate expansion factors for the estimate, the tables of population statistics are printed. At this point, the tables of population statistics will be summed to totals for groups of populations, if that option has been specified. This phase is repeated until all populations specified for the job have been processed and printed.

In the final phase, the tables of statistics for groups of populations, if any, are written and the program branches back to the beginning--the reading of the Job Control Deck for the next job. This phase is repeated until all jobs in the processing run have been completed, at which point the program is halted and the run is finished.

The program provides six processing or sampling options that are all special cases of the general case just described. The processing options consist of various combinations of the procedures contained in the first and second processing phases. Each option is described in detail later. In brief, they are:

1. Direct estimates of population parameters as simple sums of sample summaries; for example, when samples contain all elements of the population. These estimates require data input resulting from output option 1 or 2 of TABLE-2.

2. Direct estimates of population parameters as expansions of summaries from a single sample; for example, a case of simple random sampling. These estimates require data input resulting from output option 3 or 5 of TABLE-2.

3. Direct estimates of population parameters as expansions of the weighted sums of summaries from several samples, using known weights; for example, stratified random sampling from known strata. These estimates require data input resulting from output option 3 or 5 of TABLE-2.

4. Direct estimates of population parameters as expansions of the weighted sums of summaries from several samples, using estimated weights; for example, stratified random sampling with double sampling for stratification. These estimates require data input resulting from output option 3 or 5 of TABLE-2.

5. Ratio estimates of population parameters analogous to those of processing option 4, except that each cell of the tabular sample summaries is converted to a ratio of the tabular total and multiplied by an independent estimate of the tabular sample total before weighting and summing. These estimates require data input resulting from output option 4 of TABLE-2.

6. Ratio estimates of population parameters analogous to those of processing option 4, except that each cell of the tabular weighted sums of the several samples is converted to a ratio of the tabular total and multiplied by an independent estimate of the tabular (population) total before computing the final variances and expanding the statistics. These estimates require data input resulting from output option 4 of TABLE-2.

G. TABLE-2 AND OUTPUT-2 DESCRIPTION SUMMARY

The foregoing has described how TABLE-2 and OUTPUT-2 are designed to carry out a general data-reduction process and to incorporate a great many variations in detail automatically. This design makes the programs applicable to many different data-reduction problems; but their flexibility also means that they cannot provide a fully automatic solution to any problem.

The user always has the responsibility of preparing the Job Control Decks in which the particulars of a given problem are specified. The description of the decks in part II can be used as a checklist in assembling the minimal information required; but successful application of the subsystems demand, in addition, a thorough knowledge of the problems, including the end-use of the results and the origins of the data.

It will be found that the preparation and checking of the Job Control Decks is not easy. The decks contain a great deal of detailed information about the problem, not all of which can be checked by the subsystems before test runs. Consequently, while the subsystems are an efficient means of solving a variety of problems involving large amounts of data or extensive tabulations of data, other means will generally be better for simpler problems.

The special purpose of OUTPUT-2 is to compute tables of population statistics from sample summaries, according to one of several sampling schemes. The subsystem is designed to be used in tandem with TABLE-2 so that both its inputs and outputs are controlled to a large extent by the outputs of that program; therefore, it is not well adapted for independent use in applications that do not also use TABLE-2.

II. USE OF TABLE-2

A. TABLE-2 CONTROL CARD FORMATS

The description and specification of a table-compilation job is presented to the computer through a special deck of data cards referred to as the Job Control Deck. Each card in this deck contains specific pieces of information arranged in a definite format.

In this section each type of control card is described. The description gives the format of the cards, the information they must contain, and, where appropriate, the purpose and use of the required information. This section may be used both as a detailed list of instructions for coding the description of a job, and as an outline to follow in the initial stages of job specification in order that the specifications be complete.

1. Job Control Cards

The first two cards in the Job Control Deck are the TITLE CARD and the INPUT/OUTPUT CONTROL CARD. They contain the job identification and the general instructions concerning the kind of data input and output required. Both cards must always be present in the Job Control Deck. The set of job control cards is shown in figure 4.

TITLE CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-80	AAA...A	80 alphameric characters, giving a descriptive title for the job. The title will appear in the printed output.

INPUT/OUTPUT CONTROL CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-5	INPUT	Card label.
6	b	
7-9	XXX	3 numeric characters, giving the total number of data fields in each input record. The number must be <u>right-justified</u> in the field.

10	b	
11	1	The input records are in binary mode.
	2	The input records are in BCD mode on tape or disk.
	3	The input records are in BCD mode on cards.
	4	The input records are in standard CDC or IBM BCD mode on tape or disk. This option is only for the UNIVAC @ FOR system and may require modification for other systems.
	5	The records are in UNIVAC NTRAN blocked binary mode on tape. For this option, the blocking factor must be specified in columns 74-75. This option is only for the UNIVAC @ FOR system.
12	b	
13-18	XXXXXX	6 numeric characters, giving the total number of input records to be processed. The number must be <u>right-justified</u> in the field. If left blank (b) or zero (0), an end-of-file check terminates normal processing after the last record is read.
19	b	
20	X	The total number of input format cards from 1 to 5 for BCD input. This field is used only if column 11 contains a 2, 3, or 4. The use of 0 or b is interpreted as 1.
21	b	
22-27	OUTPUT	Card label.
28	b	

29	1	Construct output tables of sampling unit sums over sets of sampling units.
	2	Construct output tables of sampling unit means over sets of sampling units.
	3	Construct output tables of sampling unit means and their variances over sets of sampling units.
	4	Construct output tables of sampling unit means, their variances, and covariances of table cells with table totals over sets of sampling units.
	5	Construct output tables of sampling unit means and their variances over sets of sampling units where sampling units are selected with specified probabilities. If this option is used, the SAMPLING OPTION 5 CONTROL CARD must be used (described later).
30	b	
31	b or 0	Output written on logical unit LU2 in binary mode. This option is used for normal production processing.
	1	Output is printed in BCD (F format) on logical unit LU6. This option is used when debugging a Job Control Deck.
	2	Output written on logical unit LU2 in binary mode and also printed in BCD (F format) on logical unit LU6.
32	b	
33	b or 0	No listing of the Job Control Deck (with exception of TITLE CARD).
	1	List entire Job Control Deck.
	2	List Job Control Deck with exception of input tables.

34	b	
35-37	XXX	The number of indexing errors at which processing is to be terminated. These errors relate to row or column indexes which will not fit within specified output table dimensions. The use of b or 0 allows an unlimited number. The number must be <u>right</u> -justified in the field.
38-40	bbb	
41-45	XXXXX	The maximum number of input records per sampling unit. The number must be <u>right</u> -justified in the field. This field is required only when using PARMS.
46-48	XXX	The maximum number of subunits per sampling unit. The number must be <u>right</u> -justified in the field. This field is required only when using PARMS.
49-73	bbb...b	
74-75	XX	The blocking factor of the input data file. This field is used only if column 11 contains a 4 or 5. The number must be <u>right</u> -justified in the field. This field is required only with input option 4 or 5.
76	b	
77-80	xxx	The number of characters per record on the input data file. This field is used only if column 11 contains a 4. The number must be <u>right</u> -justified in the field. This field is required only with input option 4 or 5.

2. Input Table Cards

This section describes each type of card required in the Job Control Deck to provide the input tables used in the table indexing operations.

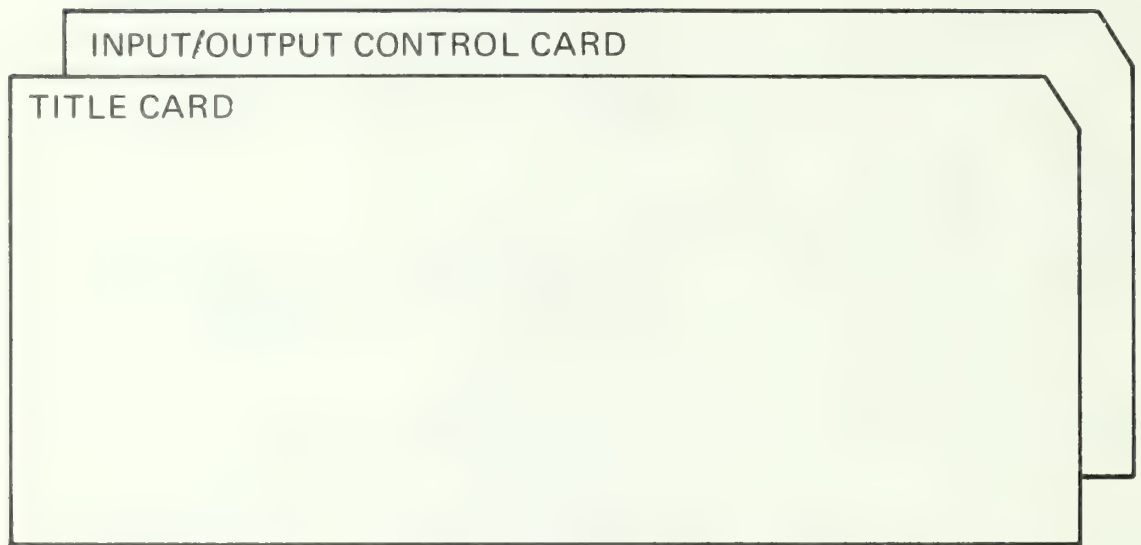


Figure 4.--Order of job control cards in the Job Control Deck for
TABLE-2

The NO INPUT TABLES CARD is to be used if the job does not require input tables for indexing. In this case no other input table cards need be used.

A maximum of 40 input tables may be put in the Job Control Deck, and the tables may be in any order. However, all tables must be placed in the Job Control Deck as a group, and the last card of the group must be the END OF INPUT TABLES CARD.

Two types of cards are required for each input table, and the cards for each input table must appear as a set. The first card of each set is the INPUT TABLE NAME CARD that gives a unique name to the table and controls the input of the table to the computer. The remaining cards of each set are repetitions of the INPUT TABLE ENTRY CARD in which a single input table entry appears. As many of these cards follow the INPUT TABLE NAME CARD as there are entries in the table. Input tables must also contain cards to allow for subtotal positions when LIST or RANGE operations are used.

Comments for use in describing the input tables or entries can be punched in the remaining columns of the two types of cards. These comments will appear in the printed output assuming the proper listing option has been selected.

The card following the last INPUT TABLE ENTRY CARD for a table must either be an INPUT TABLE NAME CARD or an END OF INPUT TABLES CARD. Input table card sets are shown in figure 5.

NO INPUT TABLES CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-4	NONE	A control word, signifying there are no input tables in the Job Control Deck.

INPUT TABLE NAME CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-4	AAAA	4 alphameric characters, giving a unique name for the input table.
5	b	
6-10	XXXXX	5 numeric characters, giving the number of entries in the table just named. The number must be <u>right-justified</u> in the field.

11	b	
12	1	There is only one field in a table entry.
	2	There are two fields in a table entry. This is required for tables to be used with the LOOKUP or RANGE operations.
13-80	AAA...A	68 alphameric characters, giving a description of the input table. The description will appear in the printed output if column 33 in the INPUT/OUTPUT CONTROL CARD contains a 1.

INPUT TABLE ENTRY CARD(S)

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-4	XXXX	4 numeric characters, containing the value of the first field of a table entry. The number must be <u>right-justified</u> in the field.
5-8	XXXX	4 numeric characters, containing the value of the second field of a table entry, if any. The value must be <u>right-justified</u> in the field. A second field is required only if the table is to be used in the LOOKUP or RANGE operations.
9-80	AAA...A	72 alphameric characters, giving a description of the input table entry. The description will appear in the printed output if column 33 in the INPUT/OUTPUT CONTROL CARD contains a 1.

END OF INPUT TABLES CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-3	END	A control word, signifying the end of all input tables. This card must always follow the last table entry card of the last input table in the Job Control Deck. This card is not used if the NO INPUT TABLES CARD has been used.

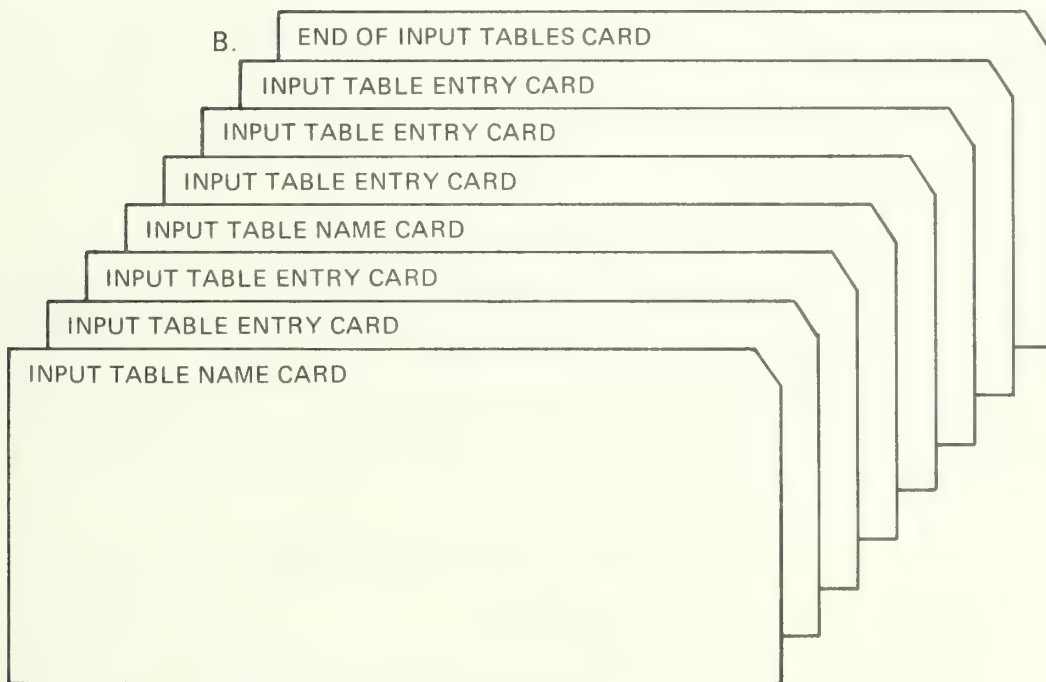
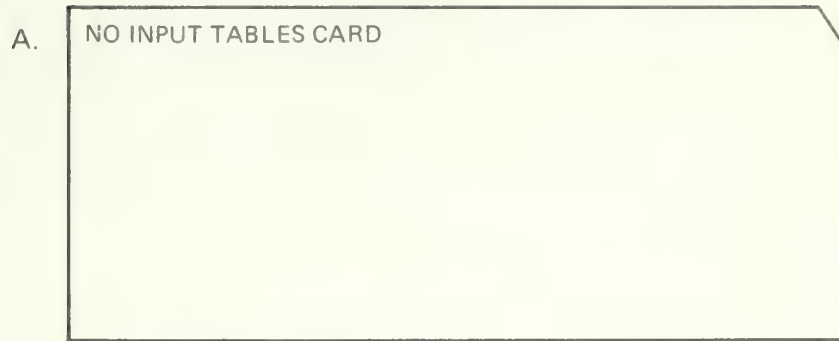


Figure 5.--Order of input table cards in the Job Control Decks;
 A, when the job does not require input tables and
 B, when the job does require input tables with two
 and three entries respectively.

3. Output Table Cards

The control cards described in this section are used to define the output tables that are to be compiled from the input data for this job. The maximum number of tables that may be defined in one run is 40 and the maximum dimensions of any table are 201 rows by 100 columns, including the row and column subtotals and totals. The definition of output tables is subject to the additional restriction that the total number of cells in all tables defined is limited by the sampling option chosen and the available storage in the computer. This restriction is discussed further in part III.

The definition of an output table gives the information required to produce the output table from the input data. The information is contained in a group of cards for each output table defined. The groups must be placed in the Job Control Deck in the order that the tables are to appear in the final output.

The first card in a group of cards defining an output table is the OUTPUT TABLE DEFINITION CARD. On this card the user assigns the table a unique name, gives its dimensions, specifies the number of entries in the table per unit record, and provides for the output of subtotals or totals, if any. Up to three OUTPUT TABLE DEFINITION CONTINUATION CARDS can be used, if necessary.

Next in the group comes a set of cards (described below) in which the table entries are defined. There must be as many of these cards as there are table entries specified on the first card. Each of the TABLE ENTRY CARDS completely defines one table entry.

Finally, the end of all output table definition cards is signaled by the END OF OUTPUT TABLES CARD. Output table definition card sets are shown in figure 6.

OUTPUT TABLE DEFINITION CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-12	DEFINEbTABLE	Card label.
13	b	
14-17	AAAA	4 alphameric characters, giving a unique name for an output table.
18	b	

19-21	XXX	3 numeric characters, giving the number of rows in the output table (including rows for subtotals but excluding a row for column totals). The number must be <u>right-justified</u> in the field.
22	A	The alphabetic character X, signifying "by", as in rows "by" columns.
23-24	XX	2 numeric characters, giving the number of columns in the output table (including columns for subtotals but excluding a column for row totals). The number must be <u>right-justified</u> in the field.
25	b	
26-27	XX	2 numeric characters, giving the total number of entries to be made in the table from each unit record (or unit record set) processed.
28	b	
29	b or 0	A row of column totals is to be produced.
	1	Suppress the row of column totals. ³
30	b or 0	A column of row totals is to be produced.
	1	Suppress the column of row totals. ³
31	b	
32	b	No subtotals.
	R	A row of subtotals is to be produced.
	C	A column of subtotals is to be produced.
33-35	XXX	The sequential number of the first row (or column) to be included in the subtotal.

³Not to be used if column 29 of the INPUT/OUTPUT CONTROL CARD contains a 4.

36-38	XXX	The sequential number of the last row (or column) to be included in the subtotal. Must be equal to or larger than the number entered in columns 3335.
39-41	XXX	3 numeric characters, giving the number of the row (or column) where the subtotal is to be placed.
42-74		Repetition of the format for columns 31-41 for up to 3 additional table subtotals. (Each set begins with a blank.)
75-79	bbbbbb	
80	b or 0	An OUTPUT TABLE DEFINITION CONTINUATION CARD does not follow.
	1	A continuation card follows with additional row or column subtotal specifications.

OUTPUT TABLE DEFINITION CONTINUATION CARD(S)

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-77	bAXXX...X	Repetition of the format for columns 31-41 on the OUTPUT TABLE DEFINITION CARD for up to 7 additional table subtotals. Up to 3 continuation cards may be used allowing a maximum of 25 subtotals to be specified. Used only if column 80 of the OUTPUT TABLE DEFINITION CARD contains a 1.
78-79	bb	
80		Repetition of the format for column 80 on the OUTPUT TABLE DEFINITION CARD.

OUTPUT TABLE ENTRY CARD(S)

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-4	AAAA	4 alphameric characters, giving the name of the output table in which the entry will be made. The name must appear exactly as given in columns 14-17 of the OUTPUT TABLE DEFINITION CARD.
5-6	bb	
7-12	LISTbb	Define the row index of the table entry as the position number, in a list of all possible values, of the value in the data field specified in columns 14-16 of this card.
	RANGEb	Define the row index of the table entry as the position number, in a list of all appropriate ranges, of the range that contains the value in the data field specified in columns 14-16 of this card.
	LOOKUP	Define the row index of the table entry as the value in a list that is paired with the value in the data field specified in columns 14-16 of this card.
	EQUATE	Define the row index of the table entry as the value in the data field specified in columns 14-16 of this card.
	CONSTb	Define the row index of the table entry as the constant contained in columns 14-16 of this card.
13	b	
14-16	XXX	3 numeric characters, giving the value required in the operation named in columns 7-12 of this card. The value must be <u>right-justified</u> in the field. If the named operation is LIST, RANGE, LOOKUP, or EQUATE, the value will be the identification number of the required data field. If the named operation is CONST, the value will be the required constant.

17	b	
18-21	AAAA	4 alphameric characters, giving the name of the input table containing the list required in the operation named in columns 7-12 of this card. The name must appear exactly as given in columns 1-4 of an INPUT TABLE NAME CARD. These columns are left blank if the operation named is EQUATE or CONST.
22	b	
23-28	AAAAAA	The same as columns 7-12, except that the operation is used to define the column index.
29	b	
30-32	XXX	The same as columns 14-16, except that the value is used to define the column index.
33	b	
34-37	AAAA	The same as columns 18-21, except that the input table is used to define the column index.
38	b .	
39-41	XXX	3 numeric characters, giving the identification number of the data field to be entered in the output table. The number must be <u>right</u> -justified in the field.
42	b	
43-45	XXX	3 numeric characters, giving the identification number of the first exception applying to the table entry. The number must be <u>right</u> -justified in the field.
46-72		Repetition of columns 43-45 format for up to 9 additional exceptions applying to the table entry.

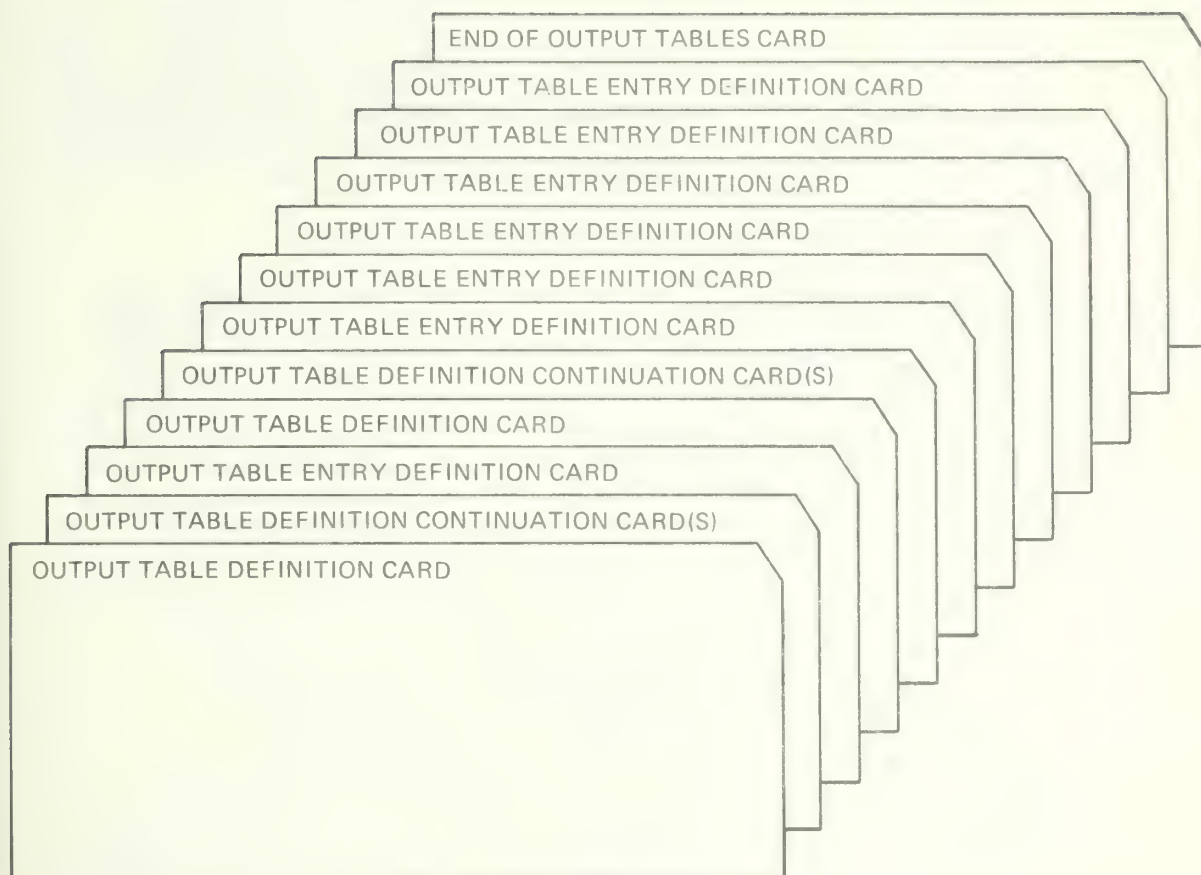


Figure 6.--Order of output definition cards in Job Control Deck.
This setup calls for two output tables, with one and
six entries respectively.

END OF OUTPUT TABLES CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-3	END	A control word, signifying the end of all output table definition and entry cards. It must follow the last entry card of the last output table.

4. Output Table Entry Exception Cards

Output table entry exceptions are used on the OUTPUT TABLE ENTRY CARDS discussed previously. Each exception to a table entry is referenced by a number. Each exception acts like a FORTRAN IF statement. Multiple exceptions on an OUTPUT TABLE ENTRY CARD act like a series of IF statements connected with the FORTRAN logical connector OR. A maximum of 100 OUTPUT TABLE ENTRY EXCEPTION CARDS may appear in the Job Control Deck. If no exceptions are used, the only card present is the NO EXCEPTIONS CARD. If exceptions are used, the last card in the exceptions card set is the END OF EXCEPTIONS CARD. The OUTPUT TABLE ENTRY EXCEPTION CARD set is shown in figure 7.

NO EXCEPTIONS CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-4	bbbb	
5-8	NONE	A control word, signifying that no OUTPUT TABLE ENTRY EXCEPTION CARDS are included in the Job Control Deck.

OUTPUT TABLE ENTRY EXCEPTION CARD(S)

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-3	XXX	3 numeric characters, giving an assigned number to the exception specified on this card. The number must be <u>right-justified</u> in the field. Up to 100 exceptions are allowed.
4	b	
5-15	NObENTRYbIF	Card label.
16	b	

17-19	XXX	3 numeric characters, giving the identification number of the data field required in the exception operation. The number must be <u>right-justified</u> in the field.
20	b	
21-22	LT	This entry is not made if the value in the data field specified in columns 17-19 is less than the value of the constant in columns 24-28 of this card.
	LE	This entry is not made if the value in the data field specified in columns 17-19 is less than or equal to the value of the constant in columns 24-28 of this card.
	EQ	This entry is not made if the value in the data field specified in columns 17-19 is equal to the value of the constant in columns 24-28 of this card.
	NE	This entry is not made if the value in the data field specified in columns 17-19 is not equal to the value of the constant in columns 24-28 of this card.
	GE	This entry is not made if the value in the data field specified in columns 17-19 is greater than or equal to the value of the constant in columns 24-28 of this card.
	GT	This entry is not made if the value in the data field specified in columns 17-19 is greater than the value of the constant in columns 24-28 of this card.
23	b	
24-28	XXXXX	5 numeric characters, giving the value of the constant required for the exception. The number must be <u>right-justified</u> in the field.

29-80	AAA...A	52 alphanumeric characters, giving a description of the exception. The description will appear in the printed output if column 33 in the INPUT/OUTPUT CONTROL CARD contains 1 or 2.
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END OF EXCEPTIONS CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-4	bbbb	
5-7	END	A control word, signifying the end of all exception cards. It must follow the last exception card in the Job Control Deck. It is not used if the NO EXCEPTIONS CARD is used.

5. Input Record Description Cards

This group of cards contains a description of the physical configuration of the input data and the kind of information contained in the data fields of each record. The individual cards are described below in the order in which they must appear in the Job Control Deck.

The first of these seven types, the input record format card(s), is optional; it is used only if the input records are written in binary coded decimal (BCD). It contains a FORTRAN format specification which describes each input data field. The format continuation cards are also optional, being used only if the complete format specification cannot be punched on the first format card.

Although the input data fields can be described by any appropriate format specification, special note should be made of the fact that values of data fields to be entered into output tables must be expressed as floating-point numbers (F format) and values of data fields to be used in setting row and column indexes and exceptions must be expressed as fixed-point numbers (I format) before the output tables can be made. If possible, therefore, data field values should be expressed properly in the input file (whether written in binary or BCD); otherwise, they will have to be converted to the proper expression using the CALCUL subroutine.

The INPUT FIELDS IDENTIFICATION CARD must always be present. It is used to record the data fields that uniquely identify the data set, the sampling unit, and the subunit, if any, to which each record in the input data belongs. A change in the value of any one of the data set

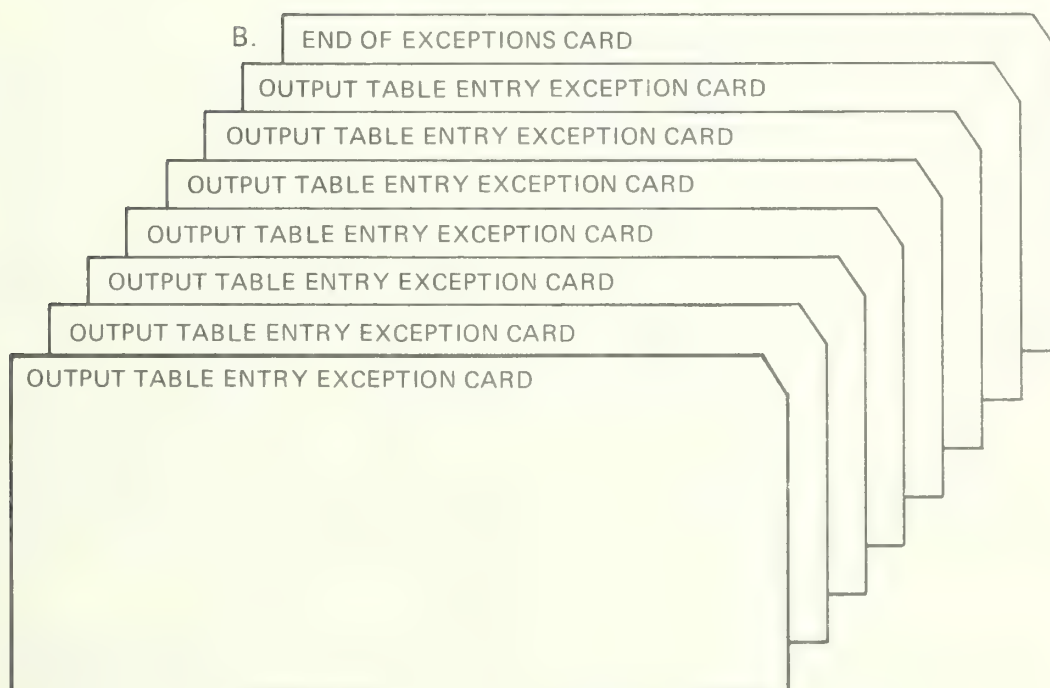


Figure 7.--Order of OUTPUT TABLE ENTRY EXCEPTION CARDS IN Job Control Deck; A, when the job does not require OUTPUT TABLE ENTRY EXCEPTION CARDS and B, when the job requires seven OUTPUT TABLE ENTRY EXCEPTION CARDS for TABLE-2

identification fields signals the end of a data set and causes the execution of the final computations and output of the summary tables for the data set. The data set identification will also appear in the output file preceding the output tables for the data set. A change in the value of any one of the sampling unit identification fields signals the end of the sampling unit input records and causes the sampling unit facsimile output tables to be summed into the data set output tables.

The INPUTS FIELDS IDENTIFICATION CARD also contains an option to search for a specific data set on the input data file. If this option is selected, an INPUT SEARCH CONTROL CARD must be included in the Job Control Deck. It is used to specify the values of the data fields that define the data set to be processed. Processing begins with the first encountered record which contains these values. Termination of processing will occur when (1) the number of records specified on the INPUT/OUTPUT CONTROL CARD has been processed, (2) an end-of-file is encountered, or (3) a record encountered contains values of the first record in the remaining data sets that are not to be processed.

The next three types of control cards are used to classify the data fields of input records according to the way that the information they contain was observed. The input record VARIABLE FIELDS CARD is used to record the identification numbers of data fields that contain attributes observed on subdivisions of subunits, or sample units if no subunits. The input record SEMIVARIABLE FIELDS CARD is used to record the identification numbers of data fields that contain attributes observed on subunits of sampling units. The input record CONSTANT FIELDS CARD is used to record the identification numbers of data fields that contain attributes observed on a sampling unit as a whole.

Every data field (input or otherwise) that is recorded in any other control card of the Job Control Deck or is used in the CALCUL subroutine must be identified on one of the above three field cards. Other data fields in the input record may also be identified in these cards, but this is optional. If a field is not identified in one of these cards, it will not be available for use by the program.

The last card in this series is the SAMPLING OPTION 5 CONTROL CARD. It is used only if output option 5 is specified on the INPUT/ OUTPUT CONTROL CARD. The card contains fields defining the number of sampling units in the sampled population and the data fields required only for option 5 processing. The set of input record description cards is shown in figure 8.

INPUT FORMAT CARD(S) (Optional)

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1	(
2-80	AAA...A	Alphameric characters containing a FORTRAN format specification that describes the format of the input records. Used only if the input records are in BCD mode. The format is continued, if necessary, on additional cards and ends with a right parenthesis in the last column used. The total number of format cards must be equal to the number specified in column 20 of the INPUT/OUTPUT CONTROL CARD. Data fields to be used in indexing operations must have I (fixed-point) specification; those to be used as table entries must have E or F (floating-point) specification; otherwise, they must be converted to the proper expression in the CALCUL subroutine.

INPUT FIELDS IDENTIFICATION CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-11	DATA b SET b ID	Card label.
12	b	
13-15	XXX	3 numeric characters, giving the identification number of the first data field of a set of data fields in which a data set is identified. The number must be <u>right-justified</u> in the field.
16-27	XXX...X	Repetition of format for columns 13-15, giving the identification numbers of up to 4 additional data fields needed to define a data set. The values for these data fields appear on the DATA INPUT IDENTIFICATION CARD in OUTPUT-2 to identify the population to be processed.
28	b	

29	b or 0	AN INPUT SEARCH CONTROL CARD is not to be used.
	1	An INPUT SEARCH CONTROL CARD follows.
30	b	
31-43	SAMPLINGbUNIT	Card label.
44	b	
45-47	XXX	3 numeric characters, giving the identification number of the first data field of a set of data fields in which a sampling unit is identified. The number must be <u>right-justified</u> in the field.
48-59	XXX...X	Repetition of format for columns 45-47, giving the identification numbers of up to 4 additional data fields needed to define a data set.
60	b	
61-68	SUBbUNIT	Card label.
69	b	
70-72	XXX	3 numeric characters, giving the identification number of the data field in which a subunit, if any, of a sampling unit is identified. The number must be <u>right-justified</u> in the field.

INPUT SEARCH CONTROL CARD (Optional)

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-5	XXXXX	5 numeric characters, giving a value of the data field specified in columns 13-15 of the INPUT FIELDS IDENTIFICATION CARD. Values for the remaining fields are given in the following columns and processing begins with the first record containing these values. The number must be <u>right-justified</u> in the field. Used only if column 29 of INPUT FIELDS IDENTIFICATION CARD contains a 1.

6-25	XXX...X	Repetition of format for columns 1-5, giving the initial values of the data fields specified in columns 16-27 of the INPUT FIELDS IDENTIFICATION CARD.
26-30	XXXXX	5 numeric characters, giving a value of the data field specified in columns 13-15 of the INPUT FIELDS IDENTIFICATION CARD. Values for the remaining fields are given in the following columns and processing terminates when one of the following conditions is reached: <ul style="list-style-type: none"> 1. The number of records specified on the INPUT/OUTPUT CONTROL CARD has been processed. 2. An end-of-file is encountered. 3. When a record containing the values specified here is encountered, processing terminates with the previous record. The number must be <u>right</u>-justified in the field.
31-50	XXX...X	Repetition of format for columns 26-30, giving the final values of the data fields specified in columns 16-27 of the INPUT FIELDS IDENTIFICATION CARD.

VARIABLE FIELDS CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-8	VARIABLE	Card label.
9-11	XXX	3 numeric characters, giving the identification number of a data field in which the values may vary from one record to another within the set of records for a sampling unit. The number must be <u>right</u> -justified in the field.
12-77	XXX...X	Repetition of format for columns 9-11, giving the identification numbers of up to 22 more variable data fields for use in processing.

78-80	bbb	Specification of variable data fields is continued on the next card.
	END	A continuation card does not follow.

VARIABLE FIELDS CONTINUATION CARD(S) (Optional)

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-8	bbbbbbbbb	
9-77	XXX...X	Same as format for columns 9-80 of the VARIABLE FIELDS CARD. Any number of continuation cards may be used.
78-80	bbb	Specification of variable data fields is continued on the next card.
	END	A continuation card does not follow.

SEMIVARIABLE FIELDS CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-8	SEMIbVAR	Card label.
9-11	XXX	3 numeric characters, giving the identification number of a data field in which the values may vary from one set of subunit records to another, and which are constant within the sets of subunit records. The number must be <u>right</u> -justified in the field.
12-77	XXX...X	Repetition of format for columns 9-11, giving the identification numbers of up to 22 more semivariable data fields for use in processing.
78-80	bbb	Specification of semivariable data fields is continued on the next card.
	END	A continuation card does not follow.

SEMIVARIABLE FIELDS CONTINUATION CARD(S) (Optional)

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-8	bbbbbbbbb	
9-77	XXX...X	Same as format for columns 9-80 of the SEMIVARIABLE FIELDS CARD. Any number of continuation cards may be used.
78-80	bbb	Specification of semivariable data fields is continued on the next card.
	END	A continuation card does not follow.

CONSTANT FIELDS CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-8	CONSTANT	Card label.
9-11	XXX	3 numeric characters, giving the identification number of a data field in which the values may vary from one sampling unit to another; and which are constant within sampling units. The number must be <u>right-justified</u> in the field.
12-77	XXX...X	Repetition of format for columns 9-11, giving the identification numbers of up to 22 more constant data fields for use in processing.
78-80	bbb	Specification of constant data fields is continued on the next card.
	END	A continuation card does not follow.

CONSTANT FIELDS CONTINUATION CARD(S) (Optional)

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-8	bbbbbbbbb	
9-77	XXX...X	Same as format for columns 9-80 of the CONSTANT FIELDS CARD. Any number of continuation cards may be used.

78-80	bbb	Specification of constant data fields is continued on the next card.
	END	A continuation card does not follow.

SAMPLING OPTION 5 CONTROL CARD (Optional)

This card is used only if column 29 of the INPUT/OUTPUT CONTROL CARD contains a 5.

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-18	NO.bSAMPLINGbUNITS	Card label.
19	b	
20-24	b or 0	Each sampling unit is wholly contained in a single data set (sampling stratum).
	XXXXX	5 numeric characters, specifying the total number of sampling units if the sampling units are subdivided into more than one data set. The number must be <u>right-justified</u> in the field. (This field <u>must</u> be b or 0 for use with OUTPUT sampling option 2.)
25-27	bbb	
28-34	AREAbID	Card label.
35	b	
36-38	XXX	3 numeric characters, specifying the identification number of the input data field containing the sampling unit area sampled within the data set (stratum). If the subunit field is blank or zero on the INPUT FIELDS IDENTIFICATION CARD, then this field must be defined on the CONSTANT FIELDS CARD. If the subunit has been specified on the INPUT FIELDS IDENTIFICATION CARD, this field may be defined on either the SEMIVARIABLE or CONSTANT FIELDS CARD. If defined at the semivariable level, then this field identifies the field containing the area of the subunit. The number must be <u>right-justified</u> .

39-41	bbb	
42-55	PROBABILITYbID	Card label.
56	b	
57-59	XXX	3 numeric characters, specifying the identification number of the input data field containing the sampling unit scaled probability of selection. This must be a constant field and defined on the CONSTANT FIELDS CARD. The number must be <u>right-justified</u> . Scaled probability is the true probability times the total number of sampling units selected.

END OF CONTROL DECK CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-19	ENDbOFbCONTROLbDECK	A control word, signifying the last card in the Job Control Deck.

DATA CARDS

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-80	XXX...X	Input data punched according to the format on the INPUT FORMAT CARD. Used only if column 11 of the INPUT/OUTPUT CONTROL CARD contains a 3 (BCD card input).

B. TABLE-2 OPERATION

This section provides information necessary to set up and process sample summarization jobs with TABLE-2. It is, in part, a summary of information given elsewhere.

1. Program Restrictions -- Standard Procedure

The TABLE-2 carries restrictions on the overall size and on certain dimensions of the problem that can be handled in a single processing run. These restrictions result primarily from the way in which the available storage capacity of the computer has been allocated to various uses in the program. However, the program has been constructed so that the more important of these allocations can readily

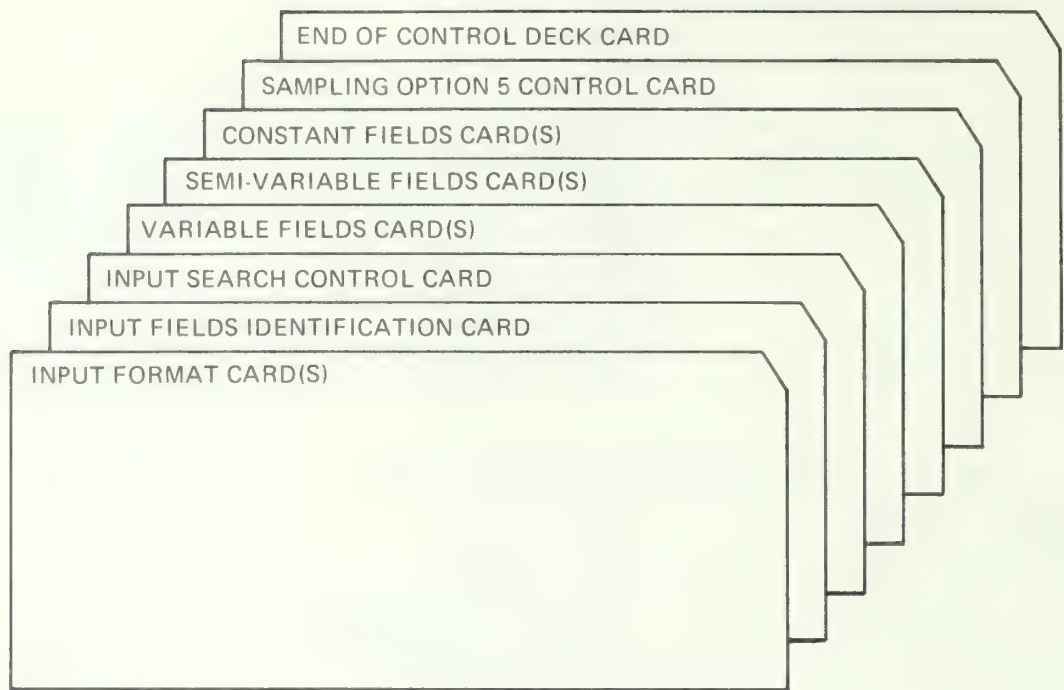


Figure 8.--Order of input record description cards in Job Control Deck

be changed if a problem of substantially different relative dimensions is encountered. The modification of dimensioned space is described in part III. The restrictions are:

- a. The number of data fields in each input record must be no greater than 132.
- b. The number of variable data fields must be no greater than 69.
- c. The number of semivariable data fields must be no greater than 69.
- d. The number of constant data fields must be no greater than 69.
- e. The number of data fields used for data set identification must be no greater than 5.
- f. The number of data fields used for sampling unit identification must be no greater than 5.
- g. The subunit identification, if any, must be contained in a single data field.
- h. The total number of cells in all input and output tables must be no greater than 10,000.
- i. The number of input tables must be no greater than 40.
- j. The number of output tables must be no greater than 40 (153 optional).
- k. The number of rows including subtotals and totals in each output table must be no greater than 201.
- l. The number of columns including subtotals and totals in each output table must be no greater than 100.
- m. The number of output table entries per record in each output table must be no greater than 10.
- n. The total number of OUTPUT TABLE ENTRY EXCEPTION CARDS must be no greater than 100.

2. Job Control Deck Setup

The Job Control Deck consists of all the punched cards through which processing specifications, necessary constants, and other data (exclusive of the data to be processed) are entered into the computer. These cards, and the logical groups into which they fall, have been described in the previous section. The assembly of the groups of control cards to form the Job Control Deck is shown in figures 9-14.

It should be noted that the monitor input deck consists of the program deck, followed by the Job Control Deck, with system control cards interspersed (fig. 15). The latter cannot be described in detail here because they vary from one computer system to another. For more information about them, see the systems representative at the computer center where the processing will be done.

3. Input Data Setup

Data input must be in the form of a single file of records. Multiple record files for a job must be grouped into a single file or be processed in multiple passes of the program. The file may be written either in binary or BCD mode.

Each record must have the same format. Values in data fields to be entered in output tables should be expressed as floating-point numbers (F format), while those in data fields to be used in setting row and column table indexes and exceptions should be expressed as fixed-point numbers (I format). Values can be changed from I to F format or vice versa in subroutine CALCUL (see part III).

The records must be sorted by sampling unit, and the sets of records for each sampling unit must be sorted by the data set (stratum) to which they belong. Additional sorting is permitted but not required. It will depend on how the output is to be used (see OUTPUT-2).

When the sampling unit attribute desired for entry into an output table is area (acres, hectares), an area constant field is required in the input file. This field is usually defined on the CONSTANT FIELDS CARD and contains an area expansion factor when using sampling option 1 and 1.0 (one unit area) when using sampling options 2, 3, and 4. The value in this field is a constant for each sample unit, or subunit of a sample unit as applied in sampling option 5.

The value is also 1.0 when using sampling option 5, except when blank or zero are not specified in columns 20-24 of the SAMPLING OPTION 5 CONTROL CARD. In this case, the area value is computed using the following formula, for each subunit of a sampling unit. This case also requires that the field containing the constant be defined as a field on the SEMIVARIABLE FIELDS card.

$$\text{Area Constant (AC)} = \frac{\sum_{k=1}^n A_{hik}}{A_{hi}} = \frac{A_{hik}}{A_{hi}} = 0 < AC \leq 1.0$$

Where: A_{hik} = area of sampling unit subunit "k" of sampling unit "i" in stratum "h".

A_{hi} = total area of sampling unit "i" in stratum "h".

n = number of sampling unit subunits in stratum "h".

4. Messages Printed During Execution

Several messages are written during normal processing. These include a listing of the Job Control Deck (if called for), the output tables (if called for), a message signifying that each input table was read correctly, messages stating that the entire Job Control Deck was read, the amount of storage specified and used, the number of records and sampling units read in each data set, the number of data sets processed, the total number of input records processed, and a list of the output tables produced.

If problems are encountered in reading the Job Control Deck or processing the data, other messages are printed. These messages are listed and explained below.

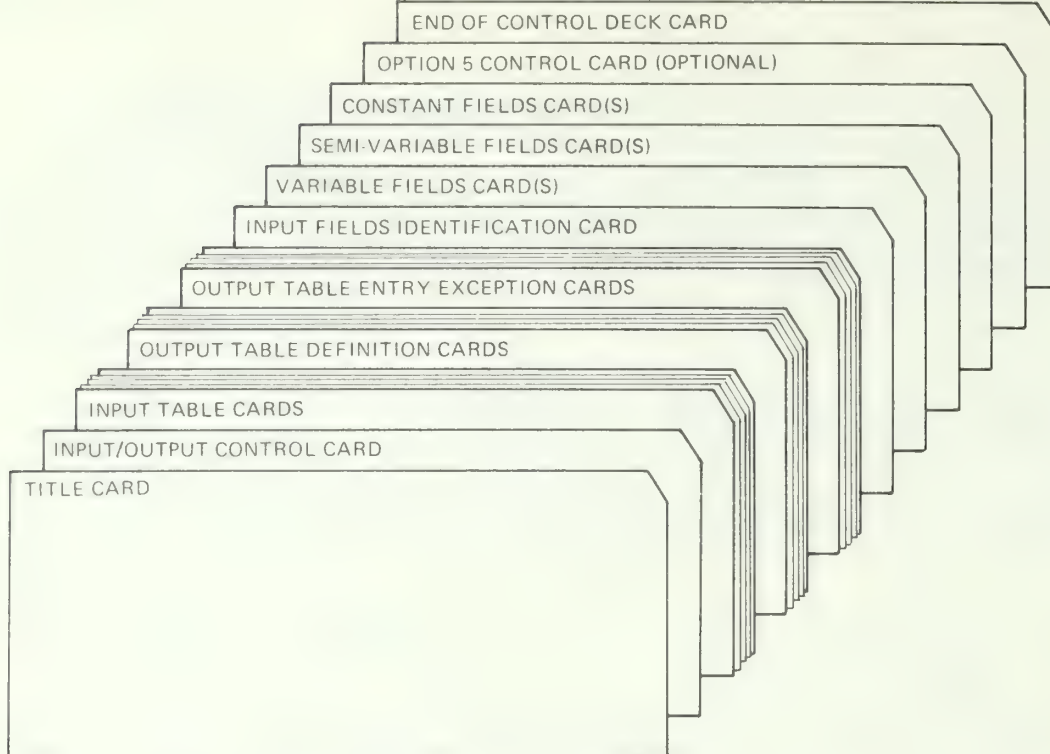


Figure 9.--TABLE-2 Job Control Deck setup for binary data tape input where processing begins on first record of input data

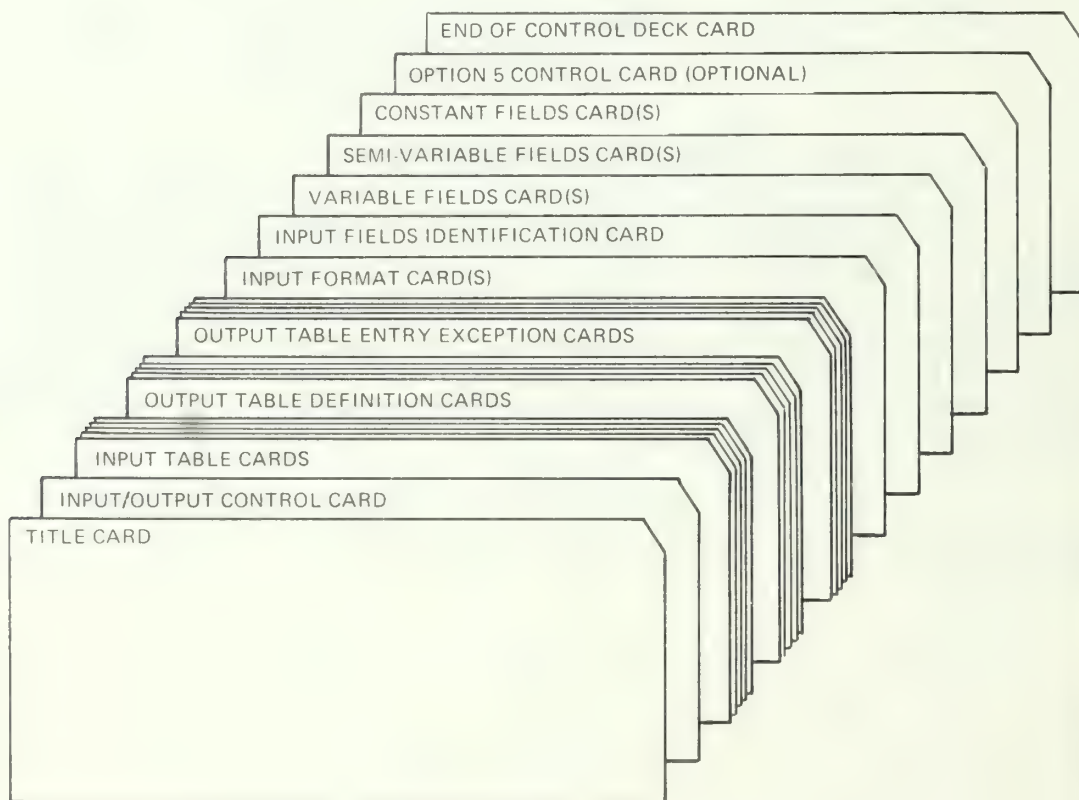


Figure 10.--TABLE-2 Job Control Deck setup for BCD data tape input where processing begins on first record of input data

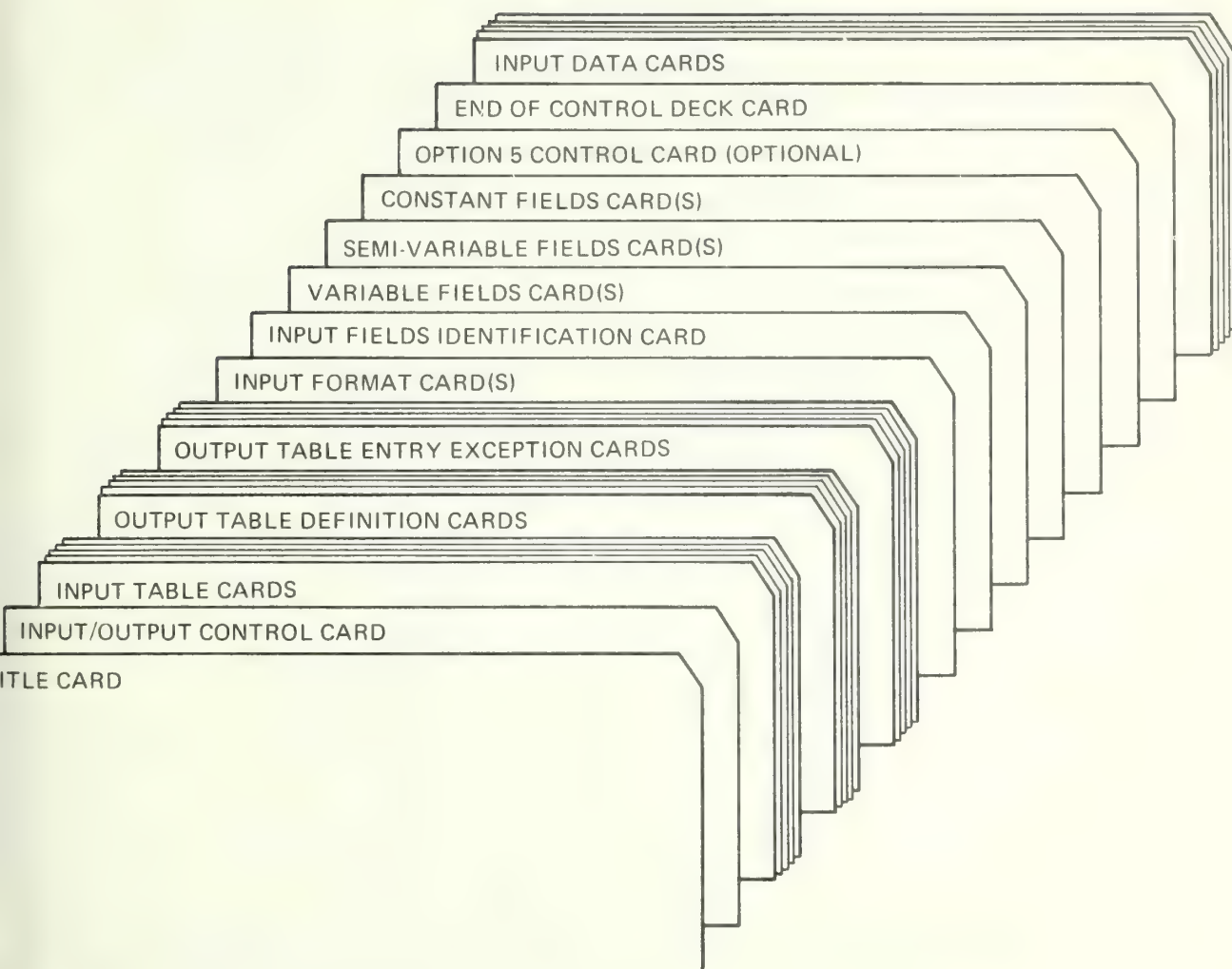


Figure 11.--TABLE-2 Job Control Deck setup for BCD data cards input where processing begins on first record of input data

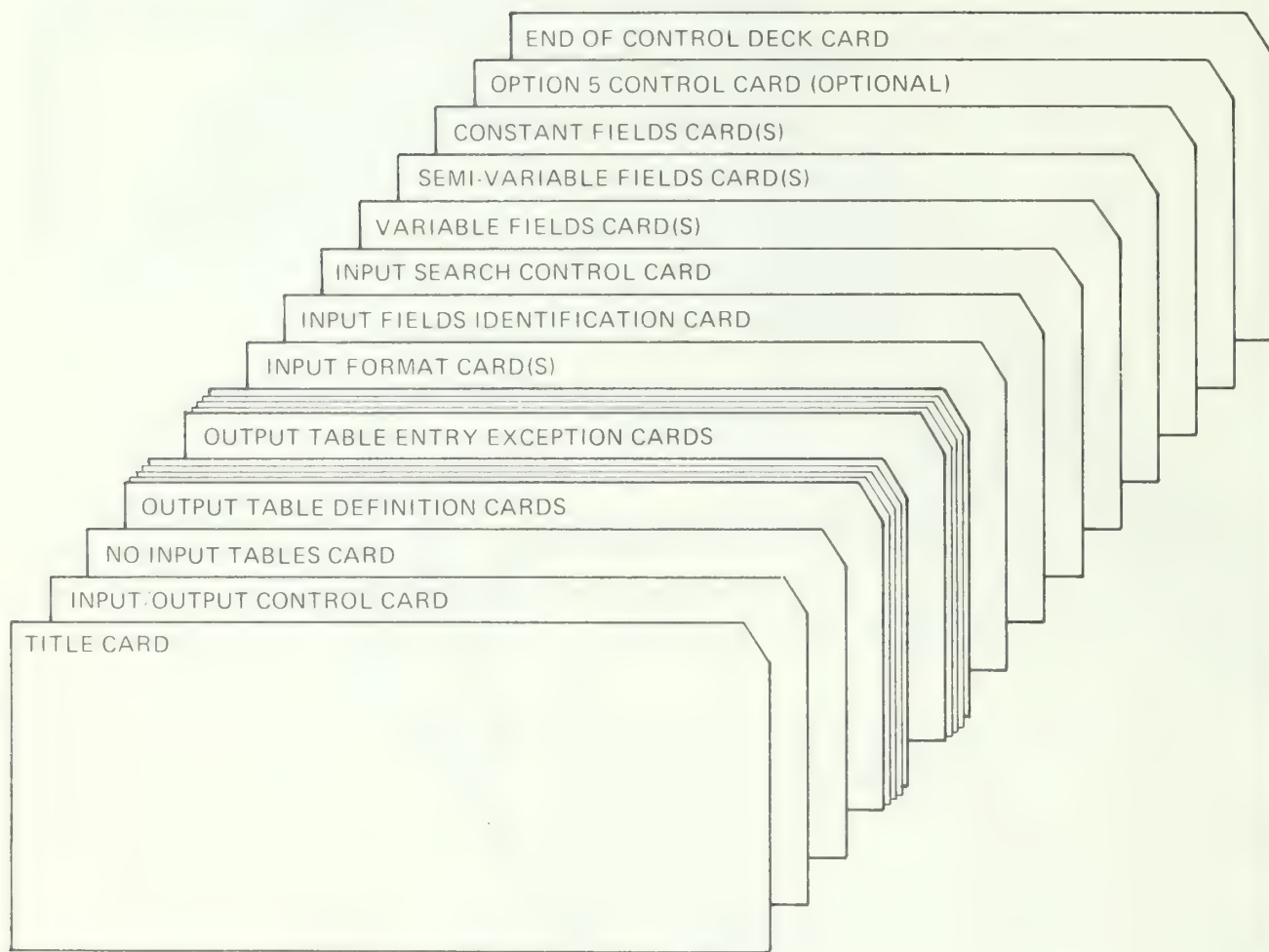


Figure 12.--TABLE-2 Job Control Deck setup for BCD data tape input with no input tables and where processing does not begin on first record of input data

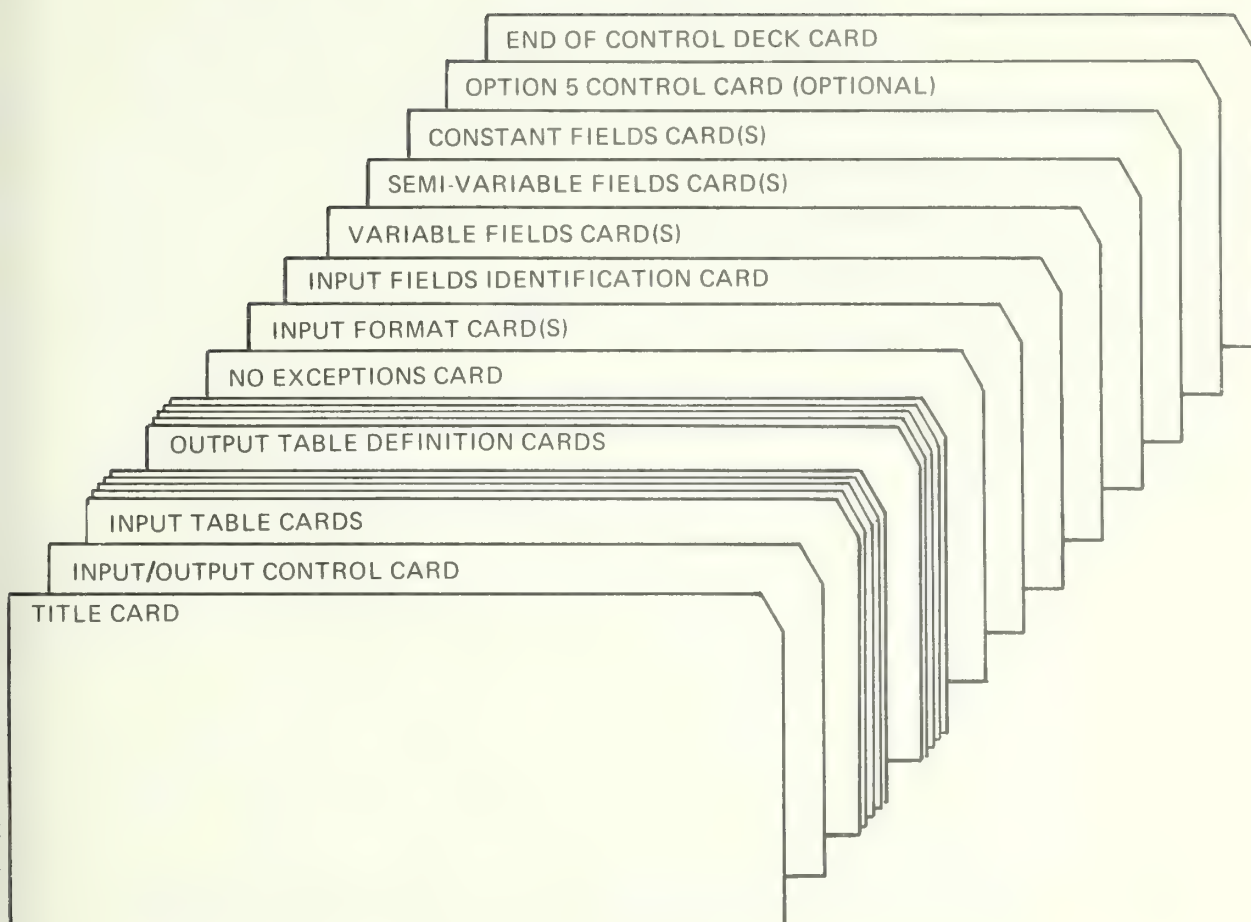


Figure 13.--TABLE-2 Job Control Deck setup for BCD data tape input with no OUTPUT TABLE ENTRY EXCEPTION CARDS where processing begins with first record of input data

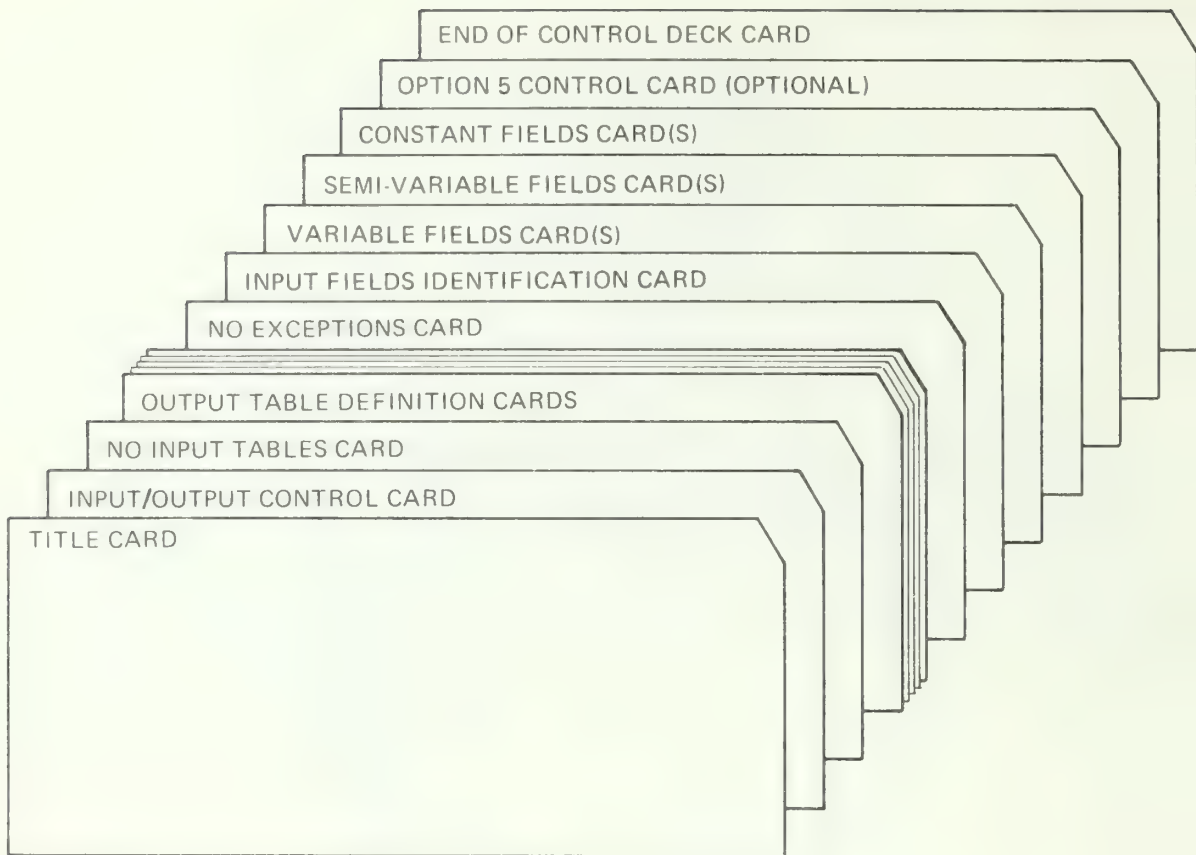


Figure 14.--TABLE-2 Job Control Deck setup for binary data tape input with no input tables, no exceptions, and where processing begins with first record of input data

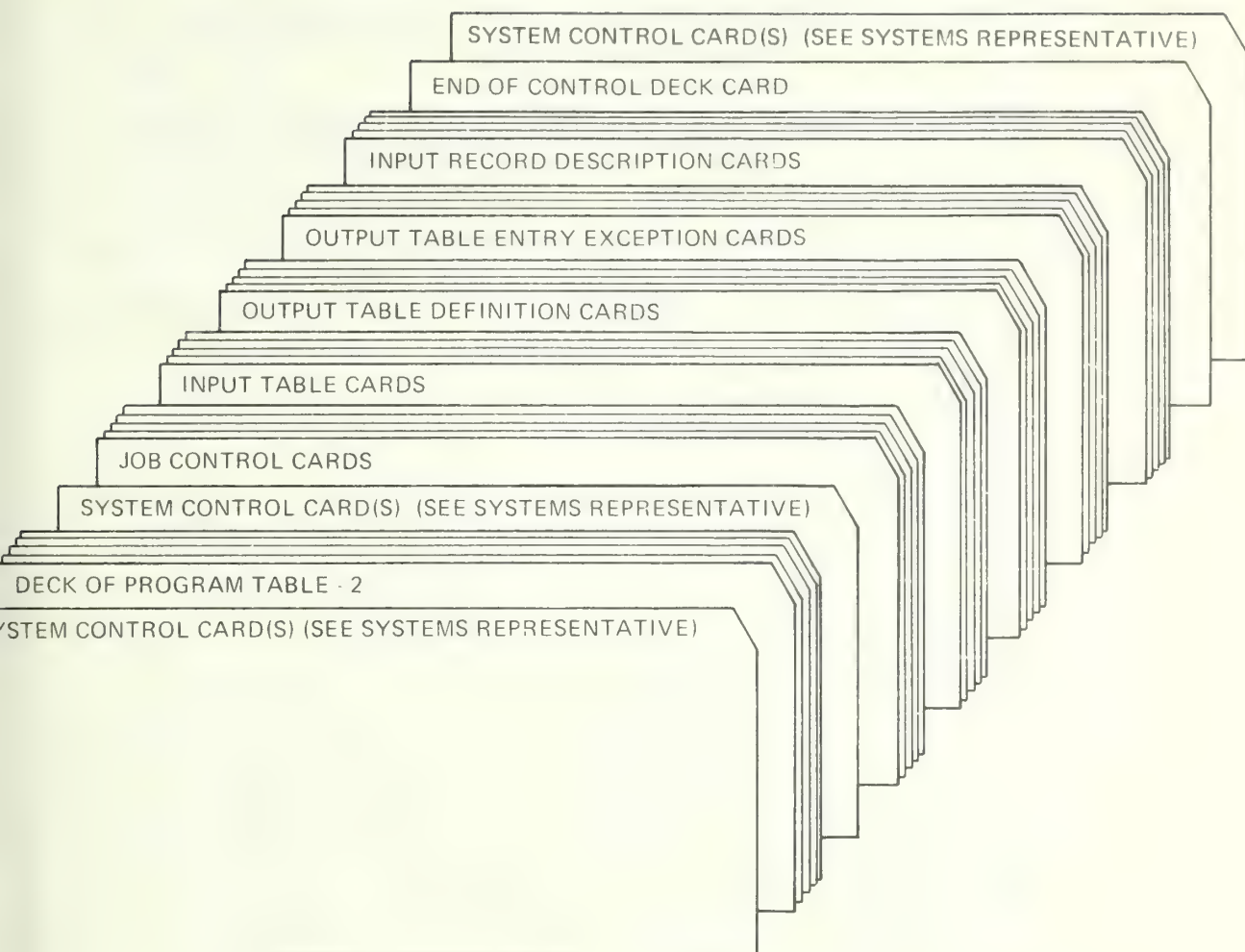


Figure 15.--Job Control Deck setup, illustrating the kinds of cards that are necessary and the order in which they must be arranged

SUB1 Messages

1. THE VALUE OF L123 IS NOT LARGE ENOUGH. THE PRESENT VALUE IS XXXX. IT MUST BE CHANGED TO XXXX.

This message is printed when L1+L2+L3 or LVAR is larger than the specified value of L123. The value of L123 and the dimension of NPOS must be set equal to the value designated in the message.

2. THE INPUT/OUTPUT CONTROL CARD IS INCORRECT.

An invalid designation has been given for a card label or field on the control card.

3. INPUT MODE 4 REQUIRES BCD TAPE BLOCKING FACTOR AND NUMBER OF CHARACTERS PER RECORD.

The BCD tape blocking factor and number of characters per record must be specified on the INPUT/OUTPUT CONTROL CARD when using input option 4.

4. INPUT MODE 5 REQUIRES BINARY TAPE BLOCKING FACTOR.

The binary tape blocking factor must be specified on the INPUT/OUTPUT CONTROL CARD when using input option 5.

5. A TABLE NAME CARD IS INCORRECT. THE TABLE NAME IS AAAA.

An invalid designation has been given for a field on a name card.

6. INPUT TABLE AAAA EXCEEDED DIMENSIONED SPACE.

The number or length of input tables must be reduced or the dimensioned space must be increased.

7. TABLE AAAA CONSISTING OF XXXXX CARDS HAS BEEN READ CORRECTLY.

This message prints each time an input table has been read successfully.

8. THE NUMBER OF ALLOWABLE OUTPUT TABLES HAS BEEN EXCEEDED. XXX HAVE BEEN CALLED FOR. XXX ARE ALLOWED.

The number of output tables must be reduced or the dimensioned space must be increased.

9. TABLE DEFINITION CARDS ARE OUT OF ORDER. TABLE AAA.

A definition card has an incorrect card label or the cards are out of order.

10. AN INVALID SPECIFICATION HAS BEEN GIVEN FOR ROW AND COLUMN TOTALS.

An invalid designation has been given for the row and column totals field on an OUTPUT TABLE DEFINITION CARD.

11. AN ILLEGAL NUMBER OF ENTRIES HAS BEEN SPECIFIED FOR TABLE AAAA. THE NUMBER OF ENTRIES IS XXX.

The number of entries must be reduced or the dimensioned space increased.

12. A SUBTOTAL SPECIFICATION IS INCORRECT.

A subtotal specification for rows or columns has been partially omitted or an invalid symbol or number has been used.

13. TABLE AAAA HAS EXCEEDED DIMENSIONED SPACE.

The number or length of output tables must be reduced or the dimensioned space must be increased.

14. AN OPERATION FOR TABLE AAAA IS INVALID. IT IS AAAAAA.

An operation for a table entry for the table named is invalid.

15. THE NAME AAAA IS NOT THE NAME OF AN INPUT TABLE.

An input table name given on an OUTPUT TABLE ENTRY CARD cannot be found in the list of input tables.

16. THE LAST EXCEPTION IS OF INCORRECT FORM OR HAS AN EXCEPTION NUMBER GREATER THAN ALLOWED. THE ALLOWED MAXIMUM = XXXX.

The last exception read (and listed if called for) contains an error. If the exception number is too large, it must be reduced or the dimensioned space increased.

17. INPUT FIELDS IDENTIFICATION CARD IS INCORRECT.

A card label is incorrect or identification data fields have not been specified for data sets or sampling units.

18. THE NUMBER OF VARIABLE FIELDS EXCEEDS THE NUMBER OF FIELDS ALLOWED FOR (xxx) OR THE LAST CARD DID NOT HAVE END IN COLS. 7880.

Correct the card or increase dimensioned space.

19. A VARIABLE FIELDS CARD IS INCORRECT.

A card label is incorrect or a negative number has been given for a data field.

20. ILLEGAL DATA FIELD xxx. THE PROGRAM HAS DIMENSION LIMIT LVAR = xxx.

A field has been defined with a value greater than the maximum number of fields allowed per input record.

21. DATA FIELD xxx HAS BEEN DEFINED AT TWO OR MORE LEVELS OR MORE THAN ONCE AT THE SAME LEVEL.

A field has been defined at more than one level for example, at both the constant and semivariable levels, or the same field appears more than once at the same level.

22. THE NUMBER OF SEMIVARIABLE FIELDS EXCEEDS THE NUMBER OF FIELDS ALLOWED FOR (xxx) OR THE LAST CARD DID NOT HAVE END IN COLS. 78-80.

Correct the card or increase dimensioned space.

23. A SEMIVARIABLE FIELDS CARD IS INCORRECT.

A card label is incorrect or a negative number has been given for a data field.

24. THE NUMBER OF CONSTANT FIELDS EXCEEDS THE NUMBER OF FIELDS ALLOWED FOR (xxx) OR THE LAST CARD DID NOT HAVE END IN COLS. 78-80.

Correct the card or increase dimensioned space.

25. A CONSTANT FIELDS CARD IS INCORRECT.

A card label is incorrect or a negative number has been given for a data field.

26. THE FIELD USED FOR EXCEPTION NO. XX HAS NOT BEEN DEFINED.

A field used for an exception has been defined with a value greater than the maximum number of fields allowed per input record, or is undefined with a value of zero, or has not been defined at the variable, semivariable, or constant level.

27. THE FIELD USED AS AN ENTRY FOR TABLE AAAA HAS NOT BEEN DEFINED AT THE VARIABLE, SEMIVARIABLE, OR CONSTANT LEVEL.

A field used for a table entry was not defined on the VARIABLE, SEMIVARIABLE, OR CONSTANT FIELDS CARDS.

28. THE FIELD USED FOR THE COLUMN INDEX FOR TABLE AAAA HAS NOT BEEN DEFINED OR IS AT A LOWER LEVEL THAN THE TABLE ENTRY.

A field used for a column index for the table specified has not been included on the VARIABLE, SEMIVARIABLE, OR CONSTANT FIELDS CARDS or was defined at a lower level than the table entry. For example, if the table entry was defined as semivariable, the field in error may have been incorrectly defined at the variable level.

29. THE FIELD USED FOR THE ROW INDEX FOR TABLE AAAA HAS NOT BEEN DEFINED OR IS AT A LOWER LEVEL THAN THE TABLE ENTRY.

A field used for a row index for the table specified has not been included on the VARIABLE, SEMIVARIABLE, OR CONSTANT FIELDS CARDS or was defined at a lower level than the table entry. For example, if the table entry was defined as semivariable, the field in error may have been incorrectly defined at the variable level.

30. THE FIELD USED FOR EXCEPTION NO. XXX HAS NOT BEEN DEFINED OR IS AT A LOWER LEVEL THAN THE TABLE ENTRY FOR TABLE AAAA ENTRY XXX.

A field used for an exception for the table entry specified has not been included on the VARIABLE, SEMIVARIABLE, OR CONSTANT FIELDS CARDS or was defined at a lower level than the table entry. For example, if the table entry was defined as semivariable, the field in error may have been incorrectly defined at the variable level. Check first to see if there is an exception card with the given number.

31. THE OPTION 5 CONTROL CARD IS INCORRECT.

An invalid designation has been given for a field on the control card. The AREA ID and PROBABILITY ID fields must contain a value greater than zero, but less than or equal to the maximum number of fields allowed per input record. The same value cannot be defined for both fields.

32. THE AREA ID MUST BE DEFINED AT THE CONSTANT LEVEL SINCE THE NUMBER OF SAMPLING UNITS IS ZERO.

The AREA ID field on the OPTION 5 CONTROL CARD must contain a value that is defined on the CONSTANT FIELDS CARD since the NO. SAMPLING UNITS field is blank or zero.

33. THE AREA ID IS NOT DEFINED AT THE CONSTANT OR SEMIVARIABLE LEVEL.

The AREA ID field on the OPTION 5 CONTROL CARD must contain a value that is defined on either the CONSTANT FIELDS CARD or the SEMIVARIABLE FIELDS CARD.

34. THE PROBABILITY ID MUST BE DEFINED AT THE CONSTANT LEVEL.

The PROBABILITY ID field on the OPTION 5 CONTROL CARD must contain a value that is defined on the CONSTANT FIELDS CARD.

35. THE END OF CONTROL DECK CARD IS INCORRECT. IT STARTS AAAA.

Cards are out of order in the Job Control Deck or the card label of the END OF CONTROL DECK CARD is incorrect.

36. THE CONTROL DECK HAS BEEN READ.

This message prints if all control cards have been read and no errors have been detected.

37. STORAGE UTILIZATION SUMMARY...

This message prints after the Job Control Deck has been read. It describes the amount of storage that has been defined for the input and output tables and the number of words of core required.

SUB2 Messages

38. READ ERROR ON INPUT TABLE.

An error has occurred while trying to read an input record using input option 4. The illegal characters must be corrected and the record reread.

39. THE NUMBER OF INPUT RECORDS IS XXX IN EXCESS OF THE XXXXX ALLOWABLE IN SAMPLING UNIT XXXXX XXXXX XXXXX XXXXX XXXXX.

Processing continues with excess records ignored. If the records must be included, the dimensioned space must be enlarged.

40. THE NUMBER OF SUBUNITS IS IN EXCESS OF THE XXX ALLOWABLE
IN SAMPLING UNIT XXXXX XXXXX XXXXX XXXXX XXXXX.

Processing continues with the records for the excess subunits ignored. If the records must be included, the subunit codes must be corrected if they are wrong or out of order, or the dimensioned space must be enlarged.

41. THE ROW INDEX CANNOT BE FOUND FOR OUTPUT TABLE AAAA, ENTRY
NO. XXX IN SAMPLING UNIT NO. XXXXX XXXXX XXXXX XXXXX XXXXX,
RECORD NO. XXXXXX. THE VALUE OF THE DATA FIELD USED TO DEFINE
THE INDEX IS XXXXX.

The entry is not made, but processing continues.

42. THE COLUMN INDEX CANNOT BE FOUND FOR OUTPUT TABLE AAAA,
ENTRY NO. XXX IN SAMPLING UNIT NO. XXXXX XXXXX XXXXX XXXXX
XXXXX, RECORD NO. XXXXXX. THE VALUE OF THE DATA FIELD USED TO
DEFINE THE INDEX IS XXXXX.

The entry is not made, but processing continues.

43. THE ROW INDEX = XXX AND IS TOO LARGE FOR OUTPUT TABLE AAAA,
ENTRY NO. XXX IN SAMPLING UNIT NO. XXXXX XXXXX XXXXX XXXXX
XXXXX, RECORD NO. XXXXXX.

The entry is not made, but processing continues.

44. THE COLUMN INDEX = XXX AND IS TOO LARGE FOR OUTPUT
TABLE AAAA, ENTRY NO. XXX IN SAMPLING UNIT NO. XXXXX XXXXX
XXXXX XXXXX XXXXX, RECORD NO. XXXXXX.

The entry is not made, but processing continues.

45. THE ROW INDEX = XXX AND IS TOO SMALL FOR OUTPUT TABLE
AAAA, ENTRY NO. XXX IN SAMPLING UNIT NO. XXXXX XXXXX XXXXX
XXXXX XXXXX, RECORD NO. XXXXXX.

The entry is not made, but processing continues.

46. THE COLUMN INDEX = XXX AND IS TOO SMALL FOR OUTPUT TABLE
AAAA, ENTRY NO. XXX IN SAMPLING UNIT NO. XXXXX XXXXX XXXXX
XXXXX XXXXX, RECORD NO. XXXXXX.

The entry is not made, but processing continues.

47. XXX ERRORS HAVE OCCURRED. PROCESSING TERMINATED.

The user-specified limit for errors associated with messages 29-34 has been reached.

48. XXXXX RECORDS AND XXXX SAMPLING UNITS WERE READ IN STRATUM
XXXXX XXXXX XXXXX XXXXX XXXXX.

This message is printed at the end of each data set processed. The data set identification is taken from the data fields defined on the INPUT FIELDS IDENTIFICATION CARD.

49. XXXXXX TOTAL RECORDS, XXXX DATA SETS HAVE BEEN PROCESSED.

This message is printed after all data sets in the population have been processed.

50. THE NAMES OF THE TABLES	NUMBER OF ROWS INCLUDING TOTALS	NUMBER OF COLUMNS INCLUDING TOTALS
<u>AAAA</u>	<u>XXX</u>	<u>XX</u>

These are summaries which are printed at the end of processing and list all output tables produced.

51.	I/O CARD VALUE ⁴	USED THIS RUN	DIFFERENCES IN
LOCATIONS MAXIMUM NUMBER OF INPUT RECORDS PER SAMPLING UNIT	<u>XXXX</u>	<u>XXXX</u>	XLEV3 <u>XXX</u> x <u>XXXX</u> = <u>XXXXXX</u>
MAXIMUM NUMBER OF SUBUNITS PER SAMPLING UNIT	<u>XXXX</u>	<u>XXXX</u>	XLEV2 <u>XXX</u> x <u>XXXX</u> = <u>XXXXXXX</u>

These are summaries which are printed at the end of processing and list the storage locations specified and used for the storage arrays for variable and semivariable fields.

C. TABLE-2 USE OF CALCULATE SUBROUTINE

TABLE-2 automatically calls a subroutine, CALCUL, once for each sampling unit. The call is executed before the performance of any table making activity for each sampling unit. The subroutine must always be present with the following as a minimum:

SUBROUTINE CALCUL(L1, L2, L3, NLEV1, XLEV1, NLEV2, XLEV2, NLEV3,
 1XLEV3, LEV2, LEV3, NRECRD, NPOINT, NOCRDS)

⁴The I/O card value printed is only meaningful for the PARMS procedure. (See TABLE-2 MODIFICATION OF DIEMNSIONED SPACE--PARMS Procedure.)


```

DIMENSION NLEV1(L1), XLEV1(L1), NLEV2(LEV2,L2),
1XLEV2(LEV2,L2), NLEV3(LEV3,L3), XLEV3(LEV3,L3)
RETURN
END

```

The user may program this subroutine to manipulate or create information for a sampling unit. Only those data fields (currently on the input file or new) which have been specified on one of the input record description cards can be used. These fields are accessed using one of three equivalenced arrays. The arrays and their relationships to the input record description cards are:

<u>Input record description card</u>	<u>Equivalenced array</u>
CONSTANT	NLEV1(*) or XLEV1(*)
SEMI VAR	NLEV2(I,*) or XLEV2(I,*)
VARIABLE	NLEV3(J,*) or XLEV3(J,*)

The * is used here to generalize for the position of the data field on the input record description card. For example, if input data field position 21 on the input file were specified as the second position on the CONSTANT FIELDS CARD, this variable would be referenced in CALCUL as NLEV1(2) or XLEV1(2), depending on the mode.

When variables are identified on the SEMIVARIABLE OR VARIABLE FIELDS CARD, the array used in CALCUL is two-dimensional. The first index identifies the sequential position of each record within a sampling unit and the second index specifies the position of the data field number on the SEMI VAR or VARIABLE card. Two counters, NPOINT and NRECRD, contain a count of the number of SEMI VAR or VARIABLE entries respectively for the sampling unit being processed. Thus the user could access each record of a sampling unit in position 2 of the VARIABLE FIELDS CARD as follows:

```

DO 100 J=1,NRECRD
WORD = XLEV3(J,2)
.
.
.
100 CONTINUE

```

A new or modified data field created in subroutine CALCUL is a temporary file change. It is available internally only as long as the appropriate array (NLEV1(*), etc.) is unchanged. Since the information in these arrays changes each time processing begins for the next sampling unit, additional programming is required if the user wishes to retain the values created. A new data file can be written with this routine to retain the modified or new data fields.

D. TABLE-2 MODIFICATION OF DIMENSIONED SPACE

The TABLE-2 carries restrictions on the dimensions and, consequently, the overall size of problem that can be handled in a single processing run. These restrictions are a result of the manner in which dimensioned space has been allocated (table 1) and the total space available in a given operating system. The program has been written so that all modifications of dimensioned space can be made in the main program called TABLE. The subprograms do not have to be changed for this purpose. The use of dimensioned space and the means of changing dimensions are discussed in detail below.

User modification of dimensioned space is not required when using the PARMS procedure with the TABLE-2 Subsystem. The PARMS procedure was developed to make the most efficient use of core storage for individual users of TABLE-2. It allows many users with different dimension requirements to use the same program without constantly determining and modifying dimension limits.

Briefly, PARMS is a FORTRAN program which creates a tailor-made TABLE-2 main program for a given Job Control Deck. The program reads the Job Control Deck and counts items such as the number of input tables, the number of output tables, and the number of exceptions. From this information PARMS determines the dimensions necessary to run the Job Control Deck. The dimensions are used to create a new main program for TABLE 2.

PARMS can extract all the dimensions needed from the Job Control Deck except the following two items: (1) the maximum number of input records per sampling unit, and (2) the maximum number of subunits per sampling unit. The user must determine these values and punch these estimates on the INPUT/OUTPUT CONTROL CARD. PARMS will use these estimates as dimension limits when it creates the new main program for TABLE-2. In turn, the TABLE-2 program will list these estimates and compare them to the values actually used in processing the data. (See TABLE-2 OPERATION, Messages Printed During Execution, Message 46.) The amount of unused core storage, if any, is shown.

Should PARMS be fed a faulty Job Control Deck, it will not print any error messages; instead, it generates a set of default dimensions and creates a new main program for TABLE-2 as previously discussed. The TABLE-2 main program will then execute and report the Job Control Deck errors.

1. Number of Input Records Per Sampling Unit

In TABLE-2, up to 150 input records may be processed per sampling unit. To change this maximum, the following steps must be taken:

Table 1.--Summary of dimensioned space restrictions, and associated program variables and arrays for TABLE-2

Item	Restriction	Variable	Arrays
Maximum number of input records per sampling unit	¹ 150	LEV3	NLEV3, XLEV3
Maximum number of subunits per sampling unit	¹ 10	LEV2	NLEV2, XLEV2
Maximum number of data fields per record	132	² LVAR	RECORD
Maximum number of variable data fields	69	² L3	NLEV3, XLEV3 LEVEL3
Maximum number of semivariable data fields	69	² L2	NLEV2, XLEV2 LEVEL2
Maximum number of constant data fields	69	² L1	NLEV1, XLEV1 LEVEL1
Maximum number of cells in all input and output tables	10,000	LTOTAL	IMP, XIMP
Maximum number of input tables	40	LIN	NTIN
Maximum number of output tables	40 (153 optional)	LOUT	NTOUT, NAMES, NCEP, ISUBT
Maximum number of rows in each output table	³ 201	Not applicable	Not applicable
Maximum number of columns in each output table	³ 101	Not applicable	Not applicable
Maximum number of exceptions	100	LEXCPS	NEXCEP
Maximum number of exceptions per table entry	10	MAX	NCEP
Maximum number of entries per table	10	MAXI	NCEP
Maximum number of subtotals (25) per table x 4, plus 4	104	LSUBT1	IMT
Maximum number of subtotals (25) per table x 4, plus 2	102	LSUBT2	ISUBT
Maximum number of data fields referenced in the program. This value must be set to the larger of LVAR or (L1+L2+L3)		L123	NPOS

¹When using the optional PARMS procedure, these values are assigned on the INPUT/OUTPUT CONTROL CARD.

²The variable L123 must always be set equal to L1+L2+L3 or LVAR, whichever is larger. The dimension of NPOS in program TABLE must be set equal to L123.

³Restricted by OUTPUT-2.

a. The variable named LEV3 must be set equal to the desired maximum value.

b. The DIMENSION statement must be changed so that the first dimension of the arrays NLEV3 and XLEV3 equals the new value of LEV3.

2. Number of Subunits Per Sampling Unit

Only 10 subunits may be processed per sampling unit. To change this maximum, the following steps must be taken:

a. The variable named LEV2 must be set equal to the desired maximum value.

b. The DIMENSION statement must be changed so that the first dimension of the arrays NLEV2 and XLEV2 equals the new value of LEV2.

3. Number of Data Fields Per Record

Up to 132 data fields may be contained in a record. To change this maximum, the following steps must be taken:

a. The variable named LVAR must be set equal to the desired maximum value.

b. The DIMENSION statement must be changed so that the dimension of the array RECORD equals the new value of LVAR.

c. If the new value of LVAR is larger than the value of the variable named L123, the variable named L123 must be set equal to the new value of LVAR and the DIMENSION statement must be changed so that the dimension of the array NPOS equals the new value of L123.

4. Number of Variable Data Fields Per Record

Up to 69 data fields may be specified as containing variable values (see VARIABLE FIELDS CARD). To change this maximum, the following steps must be taken:

a. The maximum must be a multiple of 23. The variable named L3 must be set equal to the desired maximum value plus one.

b. The DIMENSION statement must be changed so that the dimension of LEVEL3 and the second dimension of arrays NLEV3 and XLEV3 equals the new value of L3.

c. If the sum of the values of the variables named L1, L2, and L3 is larger than the value of the variable named L123, the variable named L123 must be set equal to the sum and the DIMENSION statement must be changed so that the dimension of the array NPOS equals the new value of L123.

5. Number of Semivariable Data Fields Per Record

Description is exactly the same as for the number of variable data fields per record except that, in step 1, L3 is replaced by L2; and, in step 2, LEVEL3, NLEV3, XLEV3, and L3 are replaced by LEVEL2, NLEV2, XLEV2, and L2, respectively.

6. Number of Constant Data Fields Per Record

Description is exactly the same as for the number of variable data fields per record except that, in step 1, L3 is replaced by L1; and, in step 2, LEVEL3, NLEV3, XLEV3, and L3 are replaced by LEVEL1, NLEV1, XLEV1, and L1, respectively, and "second dimension" is simply "dimension."

7. Number of Cells in All Input and Output Tables

Up to 10,000 locations are available for storing all input and output tables. To change this maximum, the following steps must be taken:

a. The variable named LTOTAL must be set equal to the desired maximum value.

b. The DIMENSION statement must be changed so that the dimension of the arrays IMP and XIMP equals the new value of LTOTAL.

The space required for storage can be computed as

$$\sum_{i=1}^m e_i + K \sum_{j=1}^n r_j c_j + (rc)_{max}$$

where

m = the total number of input tables.

e_i = the total number of entries in the i th input table.

K = a multiplier, the value of which depends on the output table option (column 29 of INPUT/OUTPUT CONTROL CARD)

<u>OPTION</u>	<u>K</u>
1 or 2	1
3	2
4	3
5	3

n = the total number of output tables.

r_j = the number of rows in the j th output table, including a row of column totals if called for.

c_j = the number of columns in the j th output table including a column of row totals if called for.

$(rc)_{max}$ = the number of cells in the largest output table.

8. Number of Input Tables

Up to 40 input tables may be used. To change this maximum, the following steps must be taken:

a. The variable named LIN must be set equal to the desired maximum value.

b. The DIMENSION statement must be changed so that the first dimension of the array NTIN equals the new value of LIN.

9. Number of Output Tables

Up to 40 output tables may be specified. To change this maximum, the following steps must be taken:

a. The variable named LOUT must be set equal to the desired maximum value.

b. The DIMENSION statement must be changed so that the first dimension of the arrays NTOU, NCEP, and ISUBT and the dimension of the array NAMES equal the new value of LOUT.

10. Number of Output Table Exceptions

Up to 100 output table exceptions may be used. To change this maximum, the following steps must be taken:

a. The variable named LEXCPS must be set equal to the desired maximum value.

b. The DIMENSION statement must be changed so that the first dimension of the array NEXCEP equals the new value of LEXCPS.

11. Number of Exceptions Per Table Entry

Up to 10 exceptions are allowed per table entry. To change this maximum, the following steps must be taken:

- a. The variable named MAX must be set equal to the desired maximum.
- b. The DIMENSION statement must be changed so that the third dimension of the array NCEP equals the new value of MAX.
- c. The FORMAT statements used for reading and printing the OUTPUT TABLE ENTRY CARD(S) must be changed to accommodate a new value of MAX if it is larger than the original value.

12. Number of Table Entries Per Output Table

Up to 10 entries are allowed per output table. To reduce this maximum, the following steps must be taken:

- a. The variable named MAXI must be set equal to the desired maximum.
- b. The DIMENSION statement must be changed so that the second dimension of the array NCEP equals the new value of MAXI.

13. Number of Subtotals Per Output Table

Up to 25 subtotals are allowed per output table. To modify this limit, the following steps must be taken:

- a. Find out the maximum number of subtotals used by any output table in the Job Control Deck.
- b. Look up the values for dimension limits LSUBT1 and LSUBT2 in the following table for the given number of subtotals:

<u>Number of subtotals</u>	<u>LSUBT1</u>	<u>LSUBT2</u>
0-4	17	18
5-11	46	46
12-18	75	74
19-25	104	102
26-32	133	130
33-39	162	158
40-46	191	186
47-53	220	214
54-60	249	242
↓	↓	↓
etc. in steps of 7	etc. in steps of 29	etc. in steps of 28

- c. Change the dimension limit of array IMT to LSUBT1.

d. Change the second dimension limit of array ISUBT to LSUBT2.

e. Change the assignment values of LSUBT1 and LSUBT2 to the new limits.

E. TABLE-2 PROGRAMING FEATURES

The following items will be of interest to programers who plan to modify the program for use on other computers or with other operating systems.

1. Tape Assignments

The logical unit assignments are as follows:

<u>Unit</u>	<u>Use</u>
LU1=1	Input file for data when tape input is used (LU1=10 for FCCC version)
LU2=2	Output file for binary tables
LU5=5	Program and Job Control Deck input and input file for data when card input is used
LU6=6	Output file for Job Control Deck listing, printed messages, and printed tables

These file assignments can be changed to fit local conditions by changing the values of variables LU1, LU2, LU5, and LU6 in the main program.

2. Subprogram Names and Functions

TABLE	Main calling program in which dimension of arrays are set. Calls subroutines SUB1 and SUB2.
SUB1	Reads and codes all cards in the Job Control Deck.
SUB2	Reads input data and forms tables for each sampling unit.
VARIAN	Computes means, variances, and covariances for data sets and writes final output tables. Called from subroutine SUB2.
CALCUL	User-written subroutine to manipulate existing data fields and generate new ones. Called from subroutine SUB2.

3. Important Arrays and Variables

The following are the principal arrays and variables used in
TABLE-2:

<u>Array</u>	<u>Dimension</u>	<u>Description</u>
IMP,XIMP	LTOTAL	Fixed- and floating-point storage array for all input and output tables.
NTIN	LINx4	Indexing information for all input tables; where LIN is the maximum number of input tables, and locations in the second dimension are used as follows: 1=The name of an input table. 2=The beginning location of a table in IMP. 3=The last location of a table in IMP. 4=The number of fields in each table entry.
NTOUT	LOUTx77	Indexing information for all output tables; where LOUT is the maximum number of output tables, and locations in the second dimension are used as follows: 1=The number of rows in an output table, including a row of column totals if called for. 2=The number of columns in an output table, including a column of row totals if called for. 3=The beginning location in XIMP of a facsimile output table less 1 less the number of rows in the table. 4=The beginning location in XIMP of a final output table, less 1 less the number of rows in the table. 5=The beginning location in XIMP of the sums of squares for a final output table, less 1 less the number of rows in the table.

- 6=The beginning location in XIMP of sums of cross-products, less 1 less the number of rows in the table.
- 7=The number of entries to be made in an output table.
- 8=The sequence number of the input table used in defining the row index for the first entry in the output table.
- 9=The code of the operation to be used in defining the row index for the first entry in the output table.
- 10=The identification number of the data field or value of the constant to be used in defining the row index for the first entry in the output table.
- 11-13=Same as 8-10, except that the information relates to defining the column index of the first entry in the output table.
- 14=The identification number of the data field to be used as the first entry in the output table.
- 15-77=Repetition of the descriptions of 8-14 for the second through tenth entries of the output table.

NEXCEP

LEXCPSx3

Storage array for table entry exceptions, where LEXCPS is the maximum number of exceptions and locations of the second dimension are used as follows:

- 1=The identification number of the data field to which an exception applies.
- 2=The value of the constant to be used in making the exception.
- 3=The operator to be used in making the exception.

NCEP

LOUTxMAXIxMAX

Indexing information for exceptions, where LOUT is the maximum number of output tables, MAXI is the maximum number of entries per table, and MAX is the maximum number of exceptions per entry.

NPOS	L123	Storage array for the storage (machine) locations of the data fields of an input record.
NLEV1, XLEV1	L1	Fixed- and floating-point storage array for data fields defined as constant fields.
NLEV2, XLEV2	LEV2xL2	Fixed- and floating-point storage array for data fields defined as semivariable fields.
NLEV3, XLEV3	LEV3xL3	Fixed- and floating-point storage array for data fields defined as variable fields.
RECORD	LVAR	Storage array into which each individual input record is read, where LVAR is the maximum number of data fields in an input record.
LEVEL1	L1	Storage array for the identification numbers of data fields defined as constant fields.
LEVEL2	L2	Storage array for the identification numbers of data fields defined as semivariable fields.
LEVEL3	L3	Storage array for the identification numbers of data fields defined as variable fields.
IDST	6	Storage array for identification numbers of the data fields defined as data set identification (DATA SET ID).
IDNOW	6	Storage array for the identification data fields for the current data set.
LIID	6	Storage array for identification numbers of the data fields defined as sampling unit identification.
LINOW	6	Storage array for the identification data fields for the current sampling unit.

L2ID	1	Storage for the identification number of the data field defined as subunit identification, if any.
L2NOW	1	Storage for the identification data field for the current subunit.
FMT	100	Storage array for the input record format.
IVAR	1	The number of data fields in each input record.
NOCRDS	1	The total number of records to be read from the input file.
IOCRDS	1	The current number of records read from the input file.
MODE	1	The mode in which the input file is to be read: 1=Binary on logical unit LU1. 2=BCD on logical unit LU1. 3=BCD on logical unit LU5 (card input).
NUNIT	1	The number of sampling units read for the current data set.
JRECRD	1	The number of records read for the current data set.
NPOINT	1	The number of subunits read for the current sampling unit.
NRECRD	1	The number of records read for the current sampling unit.
NTABLE	1	The total number of output tables defined in the Job Control Deck.
ITABLE	1	The index number of the output table currently being processed.
NAMES	LOUT	Storage array for output table names.
INDEX	2	Temporary storage for row and column indexes.

IMT	LSUBT1	Temporary storage for subtotal designations.
ISUBT	LOUTxLSUBT2	<p>Storage for subtotal designations, where LOUT is the maximum number of output tables and the second dimension is used as follows:</p> <p>1=Option for formation of a row of columns totals. 0=Construct a row of column totals. 1=Suppress column totals.</p> <p>2=Option for formation of a column of row totals. 0=Construct a column of row totals. 1=Suppress row totals.</p> <p>3=Designation of first subtotal for an output table. 0=No subtotal. 1=Row subtotal. 2=Column subtotal.</p> <p>4=First row (or column) to be included in subtotal. 5=Last row (or column) to be included in subtotal. 6=Row (or column) where subtotal is to appear in output table.</p> <p>7-102=Repetition of the designations, for 3-6 for up to 24 additional subtotals for an output table.</p>
ISETS	11	<p>Storage for values of data fields used for data set identification. The values are used to search the input file for the list of records to be used as input. The dimension is used as follows:</p> <p>1=Designation of whether a search is to be made. 0=No search; use all records. 1=Search input file for start and end of records to be used.</p> <p>2-6=Initial values of the data fields used for data set identification. Processing starts when a record with these values is found.</p>

7-11=Final values of the data fields used for data set identification. Processing terminates with the last record before the record which contains these values.

MAXI	1	The maximum number of table entries per output table.
MAX	1	The maximum number of exceptions per output table entry.
NOUTPT	1	Designation of form of output. 0=Output table written in binary on unit LU2. 1=Output tables written in BCD on unit LU6. 2=Output tables written in binary on unit LU2 and in BCD on unit LU6.
MAXERR	1	The maximum number of errors allowed in the run.
NOPT	1	The option designating how output tables are formed. 1=Sums over sets of sampling units. 2=Means over sets of sampling units. 3=Means and variances over sets of sampling units when sampling units are selected with equal probabilities. 4=Means, variances, and covariances of table cells with table totals over sets of sampling units. 5=Means and variances over sets of sampling units when sampling units are selected with unequal probabilities.

F. TABLE-2 OUTPUT TABLE FORMATS

Two alternative output table formats are available. The option is exercised in column 31 of the INPUT/OUTPUT CONTROL CARD.

In normal job processing, this column is left blank (not punched) and the table output is written on a file in binary mode. This form of output provides for rapid transmission of the output tables to OUTPUT-2 in which they may be weighted, summed, labeled, and printed or written on a tape or disk file according to the sampling and table- selection options available in OUTPUT-2.

If column 31 of the INPUT/OUTPUT CONTROL CARD is punched with a 1 or 2, the table output will be printed in BCD mode (F format). This alternative will normally be used only in debugging program changes or Job Control Decks. If punched with a 1 no further processing of the output data is possible.

The general order of the table output is the same for both alternatives. All table output from the job is in a single file. For the binary file output, this means there is only one end-of-file mark in the output file and it appears after the last record output from the job.

Within the file, the sets of output tables for each input data set are in the same order as the data sets appear in the input file. Within the data set, the output tables are in the same order as the corresponding OUTPUT TABLE DEFINITION CARDS in the Job Control Deck. The output for a given table varies with the output option given in column 29 of the INPUT/OUTPUT CONTROL CARD.

If the option is:

- 1 Only the table of sums is given for each output table.
- 2 Only the table of means is given for each output table.
- 3 or 5 The table of means, followed immediately by the table of the variances of the means, is given for each output table.
- 4 The table of means, followed immediately by the table of the variances of the means, in turn, followed immediately by the table of covariances of means, is given for each output table.

In the binary file output, three types of records are used. The first type is repeated as the first record of each data set output. The pair of records of the second and third types are repeated for every output table within the data set. The three types of records are described below:

<u>Record number</u>	<u>Word number</u>	<u>Description</u>
1	1	A number equal to one plus the number of identification words that follow in this record. This number is one greater than the number of data set identification fields specified in columns 13-27 of the INPUT FIELD IDENTIFICATION CARD.
	2	The value of the data set identification field specified in columns 13-15 of the INPUT RECORD IDENTIFICATION FIELDS CARD.
	3-6	Values of the remaining data set identification fields specified in columns 16-27 of the INPUT RECORD IDENTIFICATION FIELDS CARD.
	7	The total number of output tables for the data set which follow this record. This number is equal to the number of OUTPUT TABLE DEFINITION CARDS in the Job Control Deck.
	8	The total number of sampling units in the data set.
2	1	An output table name, as given in columns 14-17 of an OUTPUT TABLE DEFINITION CARD.
	2	The number of rows, including column subtotals and totals, in the output table named in word 1 of this record. This number is one greater than the number punched in columns 19-21 of the OUTPUT TABLE DEFINITION CARD for this output table.
	3	The number of columns, including row subtotals and totals, in the output table named in word 1 of this record. This number is one greater than the number punched in columns 23-24 of the OUTPUT TABLE DEFINITION CARD for this output table.
	4	The total length of the output table named in word 1 of this record. The value depends on the number of rows and columns in the table and the output option given in column 29 of the INPUT/OUTPUT CONTROL CARD.

3	1	The value in the first element or cell of the first column of the output table named in the preceding record 2, word 1. If the output option specified in column 29 of the INPUT/OUTPUT CONTROL CARD is 1, the value will be a sum over the sampling units of the data set. Otherwise, it will be a mean over the sampling units.
	2-r	The values in the remaining cells of the first column of the table, where r is the number of rows given in the preceding record 2, word 2.
	(r+1)-(rxc)	The values in the cells of the remaining columns of the output table, where r and c are the numbers of rows and columns given in the preceding record 2, words 2 and 3, respectively.
	((rxc)+1)-2(rxc)	The values of the variances of the cells of the output table named in the preceding record 2, word 1. These words appear in the record only if output options 3 or 4 is punched in column 29 of INPUT/OUTPUT CONTROL CARD. Otherwise, the record ends with word (rxc).
	(2(rxc)+1)-3(rxc)	The values of the covariances between the cells and the total of the output table named in the preceding record 2, word 1. These words appear in the record only if output option 4 is punched in columns 29 of the INPUT/OUTPUT CONTROL CARD. Otherwise, the record ends with word (rxc) (output options 1 and 2) or with word 2 (rxc) (output option 3).

In the printed BCD output the numbers are in floating-point format (F format). Essentially the same arrangement is followed as with the binary output, except that the output is broken into lines. There are 10 entries (or cells) per line in columnar sequence, and as many lines are printed as necessary to record all the table entries.

For example, a table that has been defined as having 10 rows and 15 columns will appear printed in the following way: line 1 will represent column 1, rows 1-10; line 2 will represent column 1, row 11; and column 2, rows 1-09. Row 11 of column 1 is the total of column 1 that has been provided by the program. The next line represents column 2, rows 10-11; and column 3, rows 1-8; and so forth through the entire table. If the option provides for tables of variances, these follow the last element of the means; and if the option provides for tables of covariances, these follow the last element of the table of variances.

The table is identified by a printed line that gives the table name, the entire number of rows and columns, and the entire number of cells represented in the printed tables. This number is merely the number of rows plus 1 times the number of columns plus 1 times the number of tables represented. If only means are printed, the number is 1; if means and variances are printed, the number is 2; if means, variances, and covariances the number is three.

G. TABLE-2 SUMMARY OF ESTIMATING PROCEDURES

In this section, the five output options available in TABLE-2 are presented in detail.

Vector notation is used to make the presentation of computing procedures compact and easy to read. An input vector, Y^I , is a one-dimensional array representing a sampling unit attribute. An output vector, Y^O , represents an output table (in general, a two-dimensional array or matrix) summarizing the sampling unit attribute. A final output vector, Y^F , represents an estimate of the population attribute that corresponds to the sampling unit attribute. Elements of these vectors are represented by y_1^I, y_1^O, y_1^F ,

It must not be inferred from what follows that the arithmetic is the arithmetic of vectors or matrices, though, in general, it is correct vector arithmetic as shown. What is implied is simply the sequential and independent application of the indicated operation to each pair of equivalent elements from the two vectors. In this sense, the procedures will generalize to the case of matrices; otherwise, they will not.

Other notational conventions adopted here are the use of a bar over an attribute symbol (\bar{Y}) to symbolize the arithmetic mean of an attribute, and the use of a dot that replaces a subscript ($Y_{.jk}$) to indicate the sum over all members of the set represented by the subscript.

OPTION 1.--Transform and Sum Sampling Unit Attributes
Over Sets of Sampling Units

Compute: $\overset{0}{Y}_{j\cdot}$.

Given: A set ($j = 1$) of $\overset{I}{Y}_{jk}$, and T

Where:

j = Subscript for the j th sample stratum or set of sampling units

k = Subscript for the k th sampling unit

$\overset{0}{Y}_{j\cdot}$ = An output vector (output table) containing the sum of the sampling unit output vectors, $\overset{0}{Y}_{jk}$, which represent a summary of the sampling unit attribute input vectors, $\overset{I}{Y}_{jk}$

$\overset{I}{Y}_{jk}$ = An input vector containing a sampling unit attribute (a data field from the input data matrix for a sampling unit)

T = A set of rules whereby the elements of the input data vector, $\overset{I}{Y}_{jk}$, are redistributed (transformed) to form the output vector $\overset{0}{Y}_{jk}$ (table), $\overset{0}{Y}_{jk}$

Procedure: $\overset{0}{Y}_{jk} = T\overset{I}{Y}_{jk}$

Output: $\overset{0}{Y}_{j\cdot} = \sum_{k=1}^P \overset{0}{Y}_{jk}$

OPTION 2.--Transform and Compute Means of Sampling Unit
Attributes Over Sets of Sampling Units

Compute: $\overset{0}{\bar{Y}}_{j\cdot}$.

Given sets of $\overset{I}{Y}_{jk}$, P_j , and T

Where:

j = Subscript for the j th sample stratum set of sampling units

k = Subscript for the k th sampling unit

$\bar{Y}_{j\cdot}^0$ = An output vector (output table) containing the arithmetic mean of the sampling unit output vectors, Y_{jk}^0 , which represent a summary of the sampling unit attribute input vectors, Y_{jk}^I

Y_{jk}^I = An input vector containing a sampling unit attribute (a data field from the input data matrix for a sampling unit)

P_j = The number of input sampling units in the stratum or set

T = A set of rules whereby the elements of the input data vector, Y_{jk}^I , are redistributed (transformed) to form the output vector (table), Y_{jk}^0

Procedure: $Y_{jk}^0 = T Y_{jk}^I$

Output: $\bar{Y}_{j\cdot}^0 = \frac{\sum_{k=1}^{P_j} Y_{jk}^0}{P_j}$

Option 3.--Transform and Compute Means and Variances of Sampling Unit Attributes Over Sets of Sampling Units

Compute: $\bar{Y}_{j\cdot}^0, V\bar{Y}_{j\cdot}^0$

Given: Sets of Y_{jk}^I, P_j , and T

Where:

j = Subscript for the j th sample stratum or set of sampling units

k = Subscript for the k th sampling unit

$\bar{Y}_{j\cdot}^0$ = An output vector (output table) containing the arithmetic mean of the sampling unit output vectors, Y_{jk}^0 , which represent a summary of the sampling unit attribute input vectors, Y_{jk}^I

$V\bar{Y}_{j\cdot}^0$ = the variance of $\bar{Y}_{j\cdot}^0$

Y_{jk}^I = An input vector containing a sampling unit attribute (a data field from the input data matrix for a sampling unit)

P_j = The number of input sampling units in the stratum or set

T = A set of rules whereby the elements of the input data vector, Y_{jk}^I , are redistributed (transformed) to form the output vector

(table), Y_{jk}^O

Procedure: $Y_{jk}^O = T Y_{jk}^I$

Output: $\bar{Y}_{j\cdot}^O = \frac{\sum_{k=1}^{P_j} Y_{jk}^O}{P_j}$

$V\bar{Y}_{j\cdot}^O = \frac{\sum_{k=1}^{P_j} (Y_{jk}^O - \bar{Y}_{j\cdot}^O)^2}{P_j (P_j - 1)}$

OPTION 4.--OPTION 3 Modified to Include Computation of Covariances for Ratio Estimates

Compute: $\bar{Y}_{j\cdot}^O$, $V\bar{Y}_{j\cdot}^O$, $C\bar{Y}_{j\cdot}^O$.

Given: Sets of Y_{jk}^I , P_j , and T

Where:

j = Subscript for the j th sample stratum or set of sampling units

k = Subscript for the k th sampling unit

$\bar{Y}_{j\cdot}^O$ = An output vector (output table) containing the arithmetic mean of the sampling unit output vectors, Y_{jk}^O , which represent a summary of the sampling unit attribute input vector Y_{jk}^I

$\overset{0}{V\bar{Y}}_{j.}$ = The variance of $\overset{0}{\bar{Y}}_{j.}$

$\overset{0}{CV}_{j.}$ = The mean covariance of output vectors for sampling units, $\overset{0}{Y}_{jk}$,
and the sums (totals) of elements in these vectors $\overset{0}{Y}_{.jk}$

$\overset{I}{Y}_{jk}$ = An input vector containing a sampling unit attribute (a data field from the input data matrix for a sampling unit)

P_j = The number of input sampling units in the stratum or set

T = A set of rules whereby the elements of the input data vector, $\overset{I}{Y}_{jk}$, are redistributed (transformed) to form the output vector

(table), $\overset{0}{Y}_{jk}$

Procedure: $\overset{0}{Y}_{jk} = T\overset{I}{Y}_{jk}$

Output: $\overset{0}{\bar{Y}}_{j.} = \frac{\sum_{k=1}^{P_j} \overset{0}{Y}_{jk}}{P_j}$

$\overset{0}{V\bar{Y}}_{j.} = \frac{\sum_{k=1}^{P_j} (\overset{0}{Y}_{jk} - \overset{0}{\bar{Y}}_{j.})^2}{P_j (P_j - 1)}$

$\overset{0}{CV}_{j.} = \frac{\sum_{k=1}^{P_j} (\overset{0}{Y}_{jk} - \overset{0}{\bar{Y}}_{j.}) (\overset{0}{y}_{.jk} - \overset{0}{\bar{y}}_{.j.})}{P_j (P_j - 1)}$

OPTION 5.--Transform and compute means and variances over sets of sampling units when sampling units are selected with unequal probabilities.¹

Compute: $A_{j\cdot}, VA_{j\cdot}, \overset{0}{Z}_{jk}, \overset{0}{VZ}_{j\cdot}, \overset{0}{Y}_{j\cdot}, \overset{0}{VY}_{j\cdot}, C\bar{V}_{j\cdot}$.

Given: Sets of $\overset{I}{Y}_{jk}, \overset{I}{PR}_{jk}, \overset{I}{A}_{jk}, P_j$, and T

Where:

j = Subscript for the j th sample stratum or data set.

k = Subscript for the k th sampling unit or portion thereof.

$\overset{I}{PR}_{jk}$ = An input vector containing the sampling unit scaled probabilities of selection. Scaled probability equals the true probability weighted by (times) the number of selected sampling units in the j th sampling stratum.

$\overset{I}{A}_{jk}$ = An input vector containing that portion of the area of the k th sampling unit that lies within the j th sampling stratum or data set.

$\overset{I}{A}_{jk}$ = An intermediate computational vector containing the area values, $\overset{I}{A}_{jk}$, each weighted inversely proportional to the respective scaled probability of selection.

$\overset{I}{A}_{j\cdot}$ = An intermediate computational vector containing the area value of the j th sampling stratum or data set.

P_j = The number of input sampling units represented in the j th sampling stratum or data set.

$\overset{I}{Y}_{jk}$ = An input vector containing sampling unit attribute values (a data field from the input data for a sampling unit)

$\overset{0}{Y}_{jk}$ = An output vector (table) which is created by redistributing (transforming) the elements of the input vector, $\overset{I}{Y}_{jk}$, by a set of rules, T .

¹Brickell, J.E. and James C. Schaefer Modifications of an inventory design using stand examinations. Res. Paper INT-____. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station: In press. Principle work deriving the estimation formulae used in Option 5. .

$\overset{0}{Z}_{jk}$ = An intermediate computational vector containing the sampling unit attribute values, $\overset{I}{Y}_{jk}$, each multiplied by the respective weighted area, A_{jk} .

$\overset{0}{Z}_{j\cdot}$ = An intermediate computational vector containing the weighted estimated total sampling unit attribute values.

$\overset{0}{\bar{Y}}_{j\cdot}$ = An output vector (table) containing sampling stratum means, each of which is a ratio of the corresponding elements of $\overset{0}{Z}_{j\cdot}$ and $A_{j\cdot}$.

$\overset{0}{VZ}_{j\cdot}$ = An intermediate computational vector containing the estimates of the variances of $\overset{0}{Z}_{j\cdot}$.

$\overset{0}{VA}_{j\cdot}$ = An intermediate computational vector containing the estimates of the variances of $A_{j\cdot}$.

$\overset{0}{CV}_{j\cdot}$ = An intermediate computational vector containing estimates of the covariances between $\overset{0}{Z}_{j\cdot}$ and $A_{j\cdot}$.

$\overset{0}{V\bar{Y}}_{j\cdot}$ = An output vector (table) containing estimates of the weighted (by probability) variances of $\overset{0}{\bar{Y}}_{j\cdot}$.

Procedure: $\overset{0}{Y}_{jk} = \overset{I}{T} \overset{I}{Y}_{jk}$; $\overset{0}{Z}_{jk} = \overset{0}{Y}_{jk} A_{jk}$; $\overset{0}{Z}_{j\cdot} = \sum_{k=1}^{P_j} \overset{0}{Z}_{jk}$

$A_{j\cdot} = \sum_{k=1}^{P_j} A_{jk}$; Where $A_{jk} = \frac{\overset{I}{A}_{jk}}{\overset{I}{PR}_{jk}}$

$VA_{j\cdot} = \frac{\sum_{k=1}^{P_j} (\overset{0}{A}_{jk})^2 - (\overset{0}{A}_{j\cdot})^2}{(P_j - 1)}$; $VZ_{j\cdot} = \frac{\sum_{k=1}^{P_j} (\overset{0}{Z}_{jk})^2 - (\overset{0}{Z}_{j\cdot})^2}{(P_j - 1)}$

$C\bar{V}_{j\cdot} = \frac{\sum_{k=1}^{P_j} (\overset{0}{Z}_{jk} \overset{0}{A}_{jk}) - (\overset{0}{Z}_{j\cdot}) (\overset{0}{A}_{j\cdot})}{(P_j - 1)}$

Output: $\frac{\overset{0}{Y}_{j\cdot}}{\overset{0}{Y}_{j\cdot}} = \frac{\sum_{k=1}^{P_j} \overset{0}{Y}_{jk} A_{jk}}{A_{j\cdot}} = \frac{\sum_{k=1}^{P_j} \overset{0}{Z}_{jk}}{A_{j\cdot}} = \frac{\overset{0}{Z}_{j\cdot}}{A_{j\cdot}}$

$\frac{\overset{0}{V\bar{Y}}_{j\cdot}}{\overset{0}{Y}_{j\cdot}^2} = \left[\frac{\overset{0}{VZ}_{j\cdot}}{(\overset{0}{Z}_{j\cdot})^2} + \frac{VA_{j\cdot}}{(\overset{0}{A}_{j\cdot})^2} - \frac{2C\bar{V}_{j\cdot}}{(\overset{0}{Z}_{j\cdot}) (\overset{0}{A}_{j\cdot})} \right]$

III. USE OF OUTPUT-2

A. OUTPUT-2 CONTROL CARD FORMATS

The description and specification of each processing job in a processing run is presented to the computer through a special deck of data cards referred to as the Job Control Deck. Each card in this deck contains specific pieces of information arranged in a definite format.

In this section, each type of control card is described. The description gives the format of the cards, the information they must contain, and, where appropriate, the purpose and use of the required information. This section may be used both as a detailed list of instructions for coding the description of a job and as an outline to follow in the initial stages of job specification in order that the specifications be complete.

1. Run Title Card

This card must be the first card in the Job Control Deck. It simply gives a descriptive title to be printed at the top of each of the job summary pages.

RUN TITLE CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-80	AAA...A	80 alphameric characters, giving a descriptive title for the entire run.

2. Job Control Cards

The job control cards are the header cards for each job in a processing run. They contain the general specifications for the job as a whole (including table labels). Each group of job control cards in the Job Control Deck is followed by other groups of cards (described below) that give detailed descriptions of job segments.

The first card in the group gives the number of populations to be processed in the job and the processing options to be used. The second card extends the output options by showing which of the sample summary tables given as input are to be processed and printed. These two cards must always be in the Job Control Deck. The other cards shown are optional and are only used when needed for a particular job.

The remaining cards of this group are used to provide labels for each table to be printed as output. These labels must always be supplied for the first job in a processing run, but they may be omitted

in any subsequent job. The last set of labels read will always be used when labels are omitted for a job. This condition requires that the NO TABLE LABELS CARD be the third and final card in the group of job control cards. If only selected tables in a table set are to be processed and printed, the ones not selected do not have to be removed from the label deck. They are bypassed during processing.

The table labels are supplied in complete sets, table by table, and in the order in which the tables occur in the input data file. A set of labels for a table can be described by two methods. The standard method consists of a TABLE TITLE CARD that contains the table name and a descriptive title; a COLUMN HEADING CARD for each column in the table (including the column of row totals at the extreme right of the table); and a ROW HEADING CARD for each row of the table (including the row of column totals at the bottom of the table). The repeat labels method consists of label sets (one set for each unique row or column label group); a TABLE TITLE CARD that contains the table name and a descriptive title; a column set card identifying the set of column labels to use in the table; and a row set card identifying the set of row labels to use in the table.

The entire group of table labels must always be followed by the END OF LABELS CARD. See figures 16-18 for the arrangement of the cards in the deck.

JOB CONTROL CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-3	JOB	Card label.
4	b	
5	b or 0	No listing of Job Control Deck.
	1	List entire Job Control Deck.
	2	List Job Control Deck with the exception of table labels.
6	b	
7	b or 0	Output to be produced in BCD on tape (logical unit LU1).
	1	Output to be produced on printer (logical unit LU6).

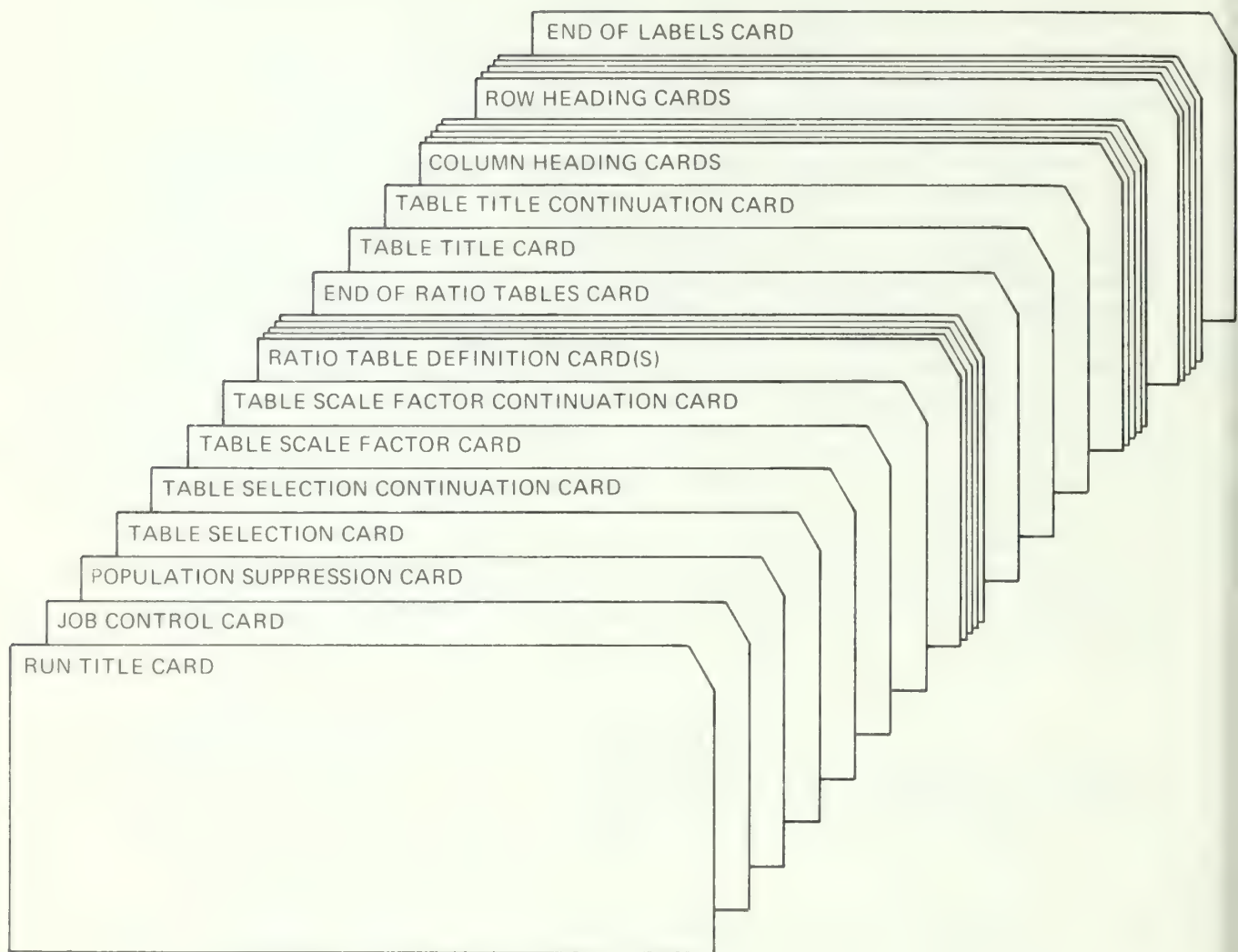


Figure 16.--Arrangement of the cards in the Job Control Deck.

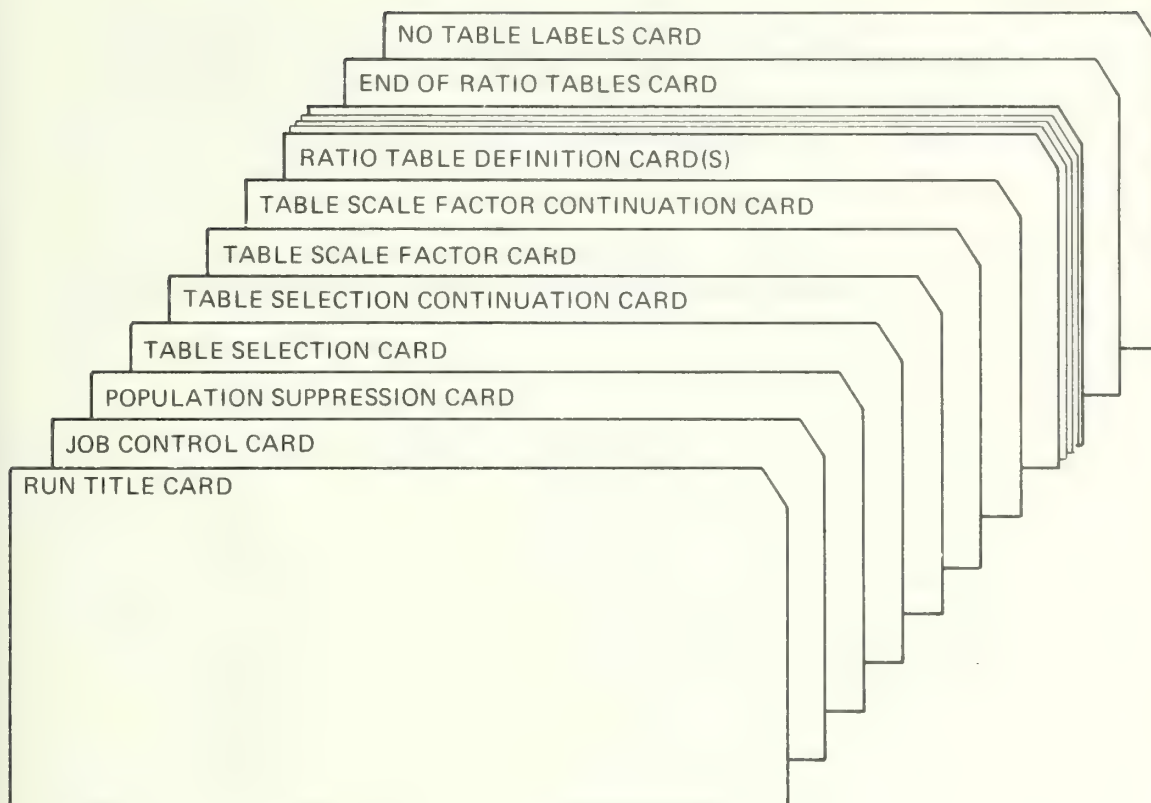


Figure 17.--Arrangement of the cards in the Job Control Deck.

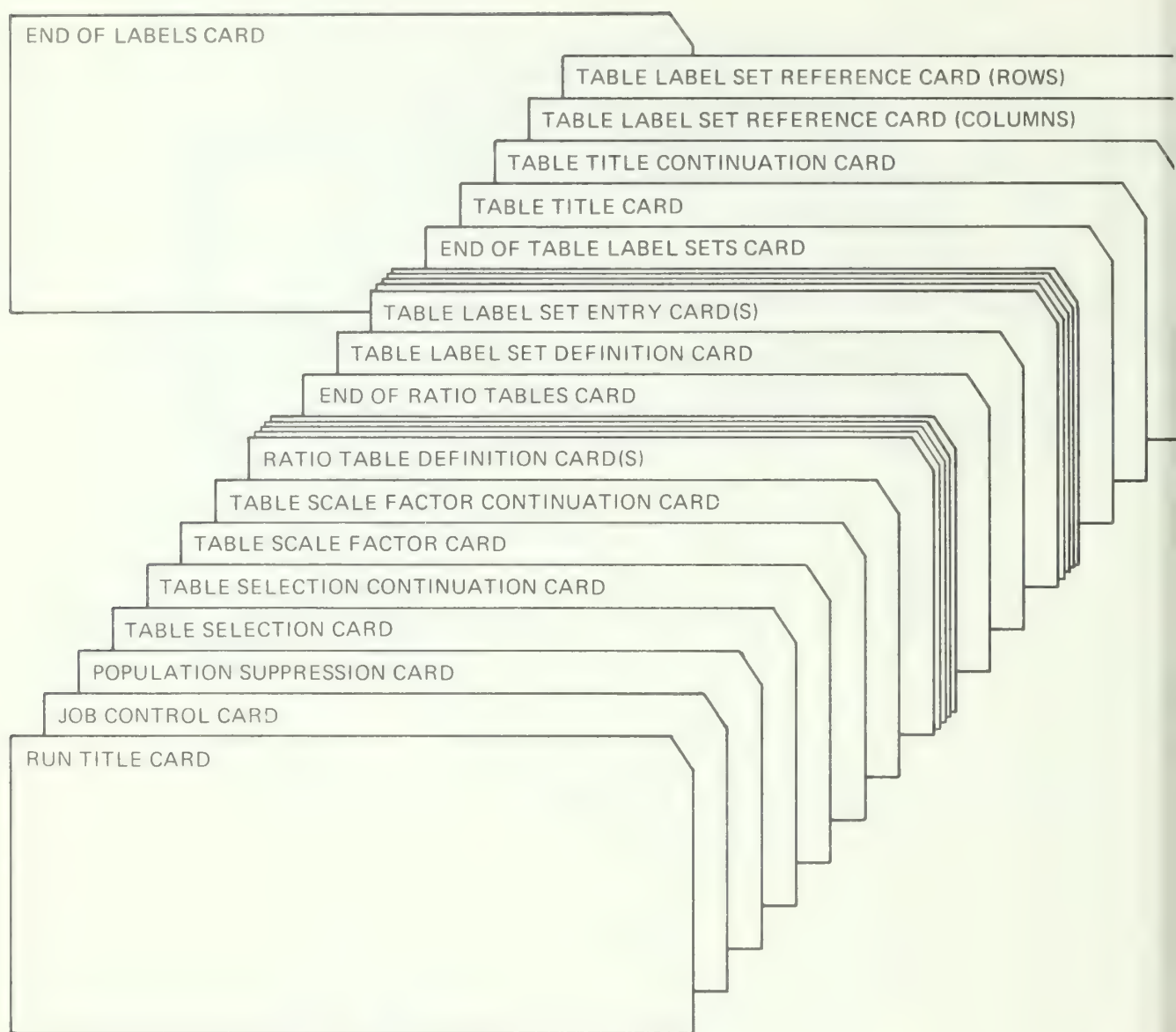


Figure 18.--Arrangement of the cards in the Job Control Deck.

8	b	
9-11	XXX	3 numeric characters, giving the number of populations to be processed in this job. The number must be <u>right</u> -justified in the field.
12	b	
13	b or 0	Do not sum the population tables over all populations in the job.
	1	Sum the population tables and print them. Print all individual population tables.
	2	Sum the population tables and print them. Do not print any individual population tables.
	3	Sum the population tables and print them. Print all individual population tables except those indicated on the POPULATION SELECTION CARD.
14	b	
15	1	The data are to be processed as a 100 percent inventory. Expansion factor must be used even if 1.0.
	2	The data are to be processed as a simple random sample.
	3	The data are to be processed as a stratified random sample with known weights.
	4	The data are to be processed as a stratified random sample with estimated stratum weights (double sampling).
	5	The data are to be processed as a stratified ratio sample with independent estimates of stratum totals and variances.
	6	The data are to be processed as a stratified ratio sample with independent estimates of totals and variances combined over all strata.

16	b	
17	b or 0	For each table specified on the TABLE SELECT CARD, do not produce tables of totals.
	1	Produce tables of totals.
18	b	
19	b or 0	For each table specified on the TABLE SELECT CARD, do not produce tables of variances.
	1	Produce tables of variances.
20	b	
21	b or 0	For each table specified on the TABLE SELECT CARD, do not produce tables of standard errors.
	1	Produce tables of standard errors.
22	b	
23	b or 0	For each table specified on the TABLE SELECT CARD, do not produce tables of standard errors as percentages of totals.
	1	Produce tables of percentages. The standard errors are expressed as percentages of corresponding totals, with an option available for producing the percentages at 1,2,3....9 standard errors.
24	b, 0, or 1	The percentages are to be calculated at one standard error.
	2,....,9	The percentages are calculated at the number of standard errors specified.
25	b or 0	The output is to be produced in floating-point E format (E20.9).
	1	The output is to be produced in floating-point F format (F20.1).

2

The output is to be produced in floating-point COMMAS format.

Examples:

0.0	--	0.0
985.3	--	985.3
3287.4	--	3,287.4
8909224.6	--	8,909,224.6
-78056.5	--	-78,056.5

3

The output is to be produced in floating-point COMMAS format with column spacing adjusted to the size of the table entries. This option has the advantage of saving paper since more columns can be squeezed onto one page. The columns are numbered and the heading associated with each number is printed in a legend at the beginning of each table. Sample printout follows:

TEST RUNS FINSYS-2 OUTPUT-2

T2-F9 AREA by LOCAL TYPE AND MAJOR TYPE
ESTIMATED TOTALS

Computer generated	{	(1) =	UNCLASSIFIED	}	Standard column labels
		(2) =	PONDEROSA PINE		
		(3) =	FIR-SPRUCE		
		(4) =	OTHER SOFTWOODS		
		(5) =	HARDWOODS		
		(6) =	TOTAL ALL TYPES		

	(1)	(2)	(3)	(4)	(5)	(6)
PONDEROSA PINE	0	40.0	0	0	0	40.0
SPRUCE	0	0	40.0	0	0	40.0
OTHER SOFTWOODS	0	0	0	0	0	.0
ASPEN	0	0	0	0	60.0	60.0
OTHER HARDWOODS	0	0	0	0	100.0	100.0
TOTAL ALL TYPES	0	40.0	40.0	0	160.0	240.0

Note: Column spacing may vary from table to table.

4

The output is to be produced in floating-point F format (F10.3) with up to 11 columns per page. Only the first 16 characters of the row labels are printed. Only columns 1-8 and 13-20 of the column labels are printed. The column headings are printed on two lines with the first 8 characters printing directly over the last 8 characters. Example follows:

Column headings...
 AAAAAAAAAA BBBBBBBB
 CCCCCCCC DDDDDDDD
 FINAL TOTAL

Row headings...
 RRRRRRRRRRRRRRRR
 XXXXYYYYZZZZ0000
 GRAND TOTAL

Table as printed...

	AAAAAAAAA	CCCCCCCC	FI
	BBBBBBBBB	DDDDDDDD	TO
RRRRRRRRRRRRRRRR	240.000	.000	240.
XXXXYYYYZZZZ0000	.000	60.000	60.
GRAND TOTAL	240.000	60.000	300.

26 b

27 b or 0

Do not scale the output

1

Scale the output for estimated totals for those tables specified on the TABLE SCALE FACTOR CARDS. (See description on page 91.)

28 b

29 b or 0

The Job Control Deck does not contain ratio tables.

1

Compute and print the ratio tables as specified on the RATIO TABLE DEFINITION CARDS. (See description on page 92.) Ratios can only be computed from estimated totals tables.

30 b

31	b, 0, or 1	Each table title consists of one TABLE TITLE CARD.
	2	Each table title consists of two TABLE TITLE CARDS.
32	b	
33	b or 0	Do not print the table name on the output tables.
	1	Print the table name offset 2 spaces from the table title on the output tables.
34	b	
35	b, 0, or 1	Single space the row entries on the output tables.
	2	Double space the row entries on the output tables.
36	b	
37	b or 0	Print 'zero' tables (normal operation).
	1	Do not print 'zero' tables.

POPULATION SELECTION CARD (Optional)

This card is only required if option 3 was selected in column 13 of the JOB CONTROL CARD.

This card, if used, is placed immediately following the JOB CONTROL CARD in the Job Control Deck.

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1	b or 0	Print all tables for the first population.
	1	Do not print any tables for the first population.
2-80	XXX...X	Continuation of the format in column 1 for the remaining populations as speci- fied in columns 9-11 of the JOB CONTROL CARD.

TABLE SELECTION CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-6	TABLES	Card label.
7	b	
8	b or 0	Do not print the first table in the data input.
	1	Produce and print the first table in the data input.
	2	Read an update table of totals to be added to the first table before printing. (Only the totals can be specified for printing, and only the updated totals will be printed. Variances, if present, apply only to the original tables.)
	3	Produce and print the first table and punch it as an update table for later processing.
	4	Read an update table of totals to be added to the first table before printing; also, punch the completed table as an update table for later processing. (Only the totals can be specified for printing, and only the updated totals will be printed.)
9-47	XXX...X	Continuation of the format for column 8 for up to 39 additional tables. If the standard dimension limits are increased; columns 48-80 on this card can be used along with 1 additional continuation card for a maximum of 153 tables. The corresponding dimension limits in OUTPUT-2 must also be increased.

TABLE SELECTION CONTINUATION CARD (Optional)

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-80	XXX...X	Continuation of designations begun on previous card for up to 80 additional tables.

TABLE SCALE FACTOR CARD (Optional)

This card is required only if option 1 was specified in column 27 of the JOB CONTROL CARD.

This card, if used, is placed immediately after the TABLE SELECT CARD(S) in the Job Control Deck.

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-6	SCALES	Card label.
7	b	
8	b or 0	Do not scale the output of the estimated totals of the first table in the data input.
	1	Scale the output of the estimated totals of the first table in the data input by a factor of 10. (Round to the nearest 10.) Example: 5678.9 -- would be printed as 567.9
	2	Same as option 1 but using a scale factor of 100.
	3	Same as option 1 but using a scale factor of 1,000.
	4	Same as option 1 but using a scale factor of 10,000.
	n	Same as option 1 but using a scale factor of 10^n when n varies from 5 to 9.
9-80	XXX...X	Continuation of the format for column 8 for up to 72 additional tables.

TABLE SCALE FACTOR CONTINUATION CARD (Optional)

This card is required only if more than 73 tables are being processed.

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-80	XXX...X	Continuation of designations begun on previous card for up to 80 additional tables.

3. Ratio Table Definition Cards

The cards described for the ratio tables are required only if column 29 of the JOB CONTROL CARD contains a 1.

RATIO TABLE DEFINITION CARD (Optional)

This card is required to define each ratio table you wish to have computed and printed.

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-4	AAAA	Alphameric name of the ratio table to be computed and printed for each population. The table title and table labels for this table must appear in the set of table labels. See page 95, item b. The two tables used in this operation must have the same dimensions.
5	=	'=' equal sign.
6-9	AAAA	Alphameric name of the table to be used as the dividend. This table must have been specified on the TABLE SELECT CARD(S).
10	/	'/' slash or divide sign.
11-14	AAAA	Alphameric name of the table to be used as the divisor. This table must have been specified on the TABLE SELECT CARD(S).

RATIO TABLE DEFINITION CONTINUATION CARD(S) (Optional)

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-14		Repetition of the format on the RATIO TABLE DEFINITION CARD. Up to 49 continuation cards may be used allowing a maximum of 50 ratio tables to be specified.

END OF RATIO TABLE DEFINITION CARD (Optional)

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-3	END	A control word signifying the end of all ratio tables. This card must always follow the last ratio table that is specified.

4. Table Labels Cards

This section describes the cards necessary to define each table's title, column, and row headings. This group of cards appears in the Job Control Deck immediately after the TABLE SELECT CARD(S). The optional TABLE SCALE FACTOR CARD and RATIO TABLE CARD(S), if used, follow the TABLE SELECT CARD(S) and precede the table labels cards.

The table labels may be specified in three ways; no labels, standard, or repeat labels. OUTPUT-2 writes the table labels on a scratch file, unit LU3=3.

a. No Labels Specification

Use this form for secondary jobs when stacking several jobs in one run. The first job must define the table labels.

NO TABLE LABELS CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
19	NOBLABELS	A card label, signifying that table labels are not in the Job Control Deck for the job. This card cannot be used for the first job of a run, because the labels must be present for that job. However, in subsequent jobs using the same labels, this card may be used. (This card can be used for the first job only if the user writes his own file of table labels to use in place of the scratch file, LU3=3.)

b. Standard Labels Specification

This form consists of a group of cards for each table. The first card of the group is for the table title. (Two cards may be used. See JOB CONTROL CARD options for column 31.) Following the table title are cards to describe the column headings, one card per column heading. Following the column heading cards are the row heading cards, one card per row heading.

The labels must appear in the order of their appearance on the TABLE SELECT CARD(S). Ratio tables, if used, must be defined after the regular tables and in the same order as defined on the RATIO TABLE DEFINITION CARD(S). The last card of the table labels must be the END OF LABELS CARD.

TABLE TITLE CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-4	AAAA	4 alphameric characters, giving a unique name by which a table may be referenced. The name must be <u>left-justified</u> in the field and must appear exactly as given on the OUTPUT TABLE DEFINITION CARD used in TABLE-2.
5-80	AAA...A	76 alphameric characters, giving a descriptive title for a table.

TABLE TITLE CONTINUATION CARD (Optional)

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-80	AAA...A	Continuation of previous card for up to 80 additional characters for the table title. Used only if column 31 of the JOB CONTROL CARD contains a 2.

COLUMN HEADING CARDS

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-20	AAA...A	20 alphameric characters, giving a label for a column in an output table. The label should be <u>right-justified</u> in the field. There must be 1 card for each column of the table, and the last card of the group must be the label for the column of row totals (if totals were produced in TABLE-2).

ROW HEADING CARDS

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-20	AAA...A	20 alphameric characters, giving a label for a row in an output table. The label should be <u>left-justified</u> in the field. There must be 1 card for each row of the table, and the last card of the group must be the label for the row of column totals (if totals were produced in TABLE-2).
21	b or 0	Do not skip any lines after printing this row heading.
	1	Skip 1 line after printing this row heading. This option is usually used to set off subtotals.
	n	Skip n lines after printing this row heading where n varies from 2-9.

c. Repeat Labels Specification

This form is similar to the standard specification except that it usually takes fewer cards. The last card of the table labels must still be the END OF LABELS CARD and the cards for the table titles remain the same, but the column and row heading cards are replaced by references to sets of heading cards. Two TABLE LABEL SET REFERENCE CARDS are required for each table and these cards appear immediately after the TABLE TITLE CARD(S). The first reference card defines the set of column headings while the second reference card defines the set of row headings to use. The user defines these reference sets before the table titles. When the repeat labels specification is used, all row and column labels must appear as sets before the first TABLE TITLE CARD.

Three types of cards are necessary to define the reference sets. The TABLE LABEL SET DEFINITION CARD is used to assign a reference name to the set. The TABLE LABEL SET ENTRY CARDS make up the members of the set. These entry cards are identical to the COLUMN HEADING CARDS and ROW HEADING CARDS of the standard specification. The END OF TABLE LABEL SETS CARD is used to signal the end of all set definitions.

TABLE LABEL SET DEFINITION CARD (Optional)

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-4	****	4 control characters.
5-8	AAAA	4 alphanumeric characters, giving a unique name for the table label set.

TABLE LABEL SET ENTRY CARDS (Optional)

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-20/1-21	AAA...A/AAA...AX	The same as columns 1-20 on the COLUMN HEADING CARDS or 1-21 on the ROW HEADING CARDS depending on which set is being defined.

END OF TABLE LABEL SETS CARD (Optional)

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-8	*****	8 control characters, signaling the end of all table label reference set definitions.

TABLE LABEL SET REFERENCE CARD (Optional)

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-4	bbbb	
5-8	AAAA	4 alphanumeric characters, specifying the name of the table label set to use for the column or row labels.

Following is an example of the same set of table labels specified under the standard and repeat labels methods:

Standard Labels Specification

T001TABLE 1 TITLE
 BLUE
 RED
 YELLOW
 ORANGE

1-10
 11-20
 21-30

T002TABLE 2 TITLE
 SMALL
 MEDIUM
 LARGE

1-10
 11-20
 21-30

T003TABLE 3 TITLE
 BLUE
 RED
 YELLOW
 ORANGE

A
 B
 C
 D
 E
 F
 G
 H

T004TABLE 4 TITLE
 SMALL
 MEDIUM
 LARGE

A
 B
 C
 D
 E
 F
 G
 H

END OF LABELS

Repeat Labels Specification

****SET1

BLUE
 RED
 YELLOW
 ORANGE

****SET2

1-10
 11-20
 21-30

****SET3

SMALL
 MEDIUM
 LARGE

****SET4

A
 B
 C
 D
 E
 F
 G
 H

T001TABLE 1 TITLE

SET1

SET2

T002TABLE 2 TITLE

SET3

SET2

T003TABLE 3 TITLE

SET1

SET4

T004TABLE 4 TITLE

SET2

SET4

END OF LABELS

END OF LABELS CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-13	ENDbOFbLABELS	A control word, signifying the end of the deck of table labels. Not used if the NO TABLE LABELS CARD was used.

5. Population Description Cards

The control cards described in this section contain all of the information that is relevant in describing a population as a whole. There must be one group of these cards for each population to be processed in a job. The arrangement of the individual cards in the group for one population is shown in figure 19.

The POPULATION TITLE CARD must always be the first card in the group. It simply contains a descriptive title for the population that will be printed at the top of every page of output for that population.

The DATA INPUT IDENTIFICATION CARD must always be the next card in the group. It contains the identification of the first sample (stratum) to be processed for the population, exactly as it is in the input data file. The identification is used to search the input file for the required sample summary tables. If there is more than one sample for a population, it is assumed that the input data for the additional samples follow immediately after the identified sample in the input file.

The EXPANSION FACTOR CARD is third in the group, and it too must always be included. In addition to the expansion factor by which the population mean is to be multiplied, it contains the number of samples to be processed for the population and the sum of the sample weights.

The POPULATION TABLE TOTALS CARD(S) is used only when processing option 6 is specified in columns 19-21 of the JOB CONTROL CARD. It contains the independent estimates of the population grand mean and grand variance for each one of the output tables. These cards must be ordered as are the equivalent sample summary tables in the input data file created in TABLE-2. Update tables are inserted, when appropriate, before the POPULATION TITLE CARD for the next population, if any.

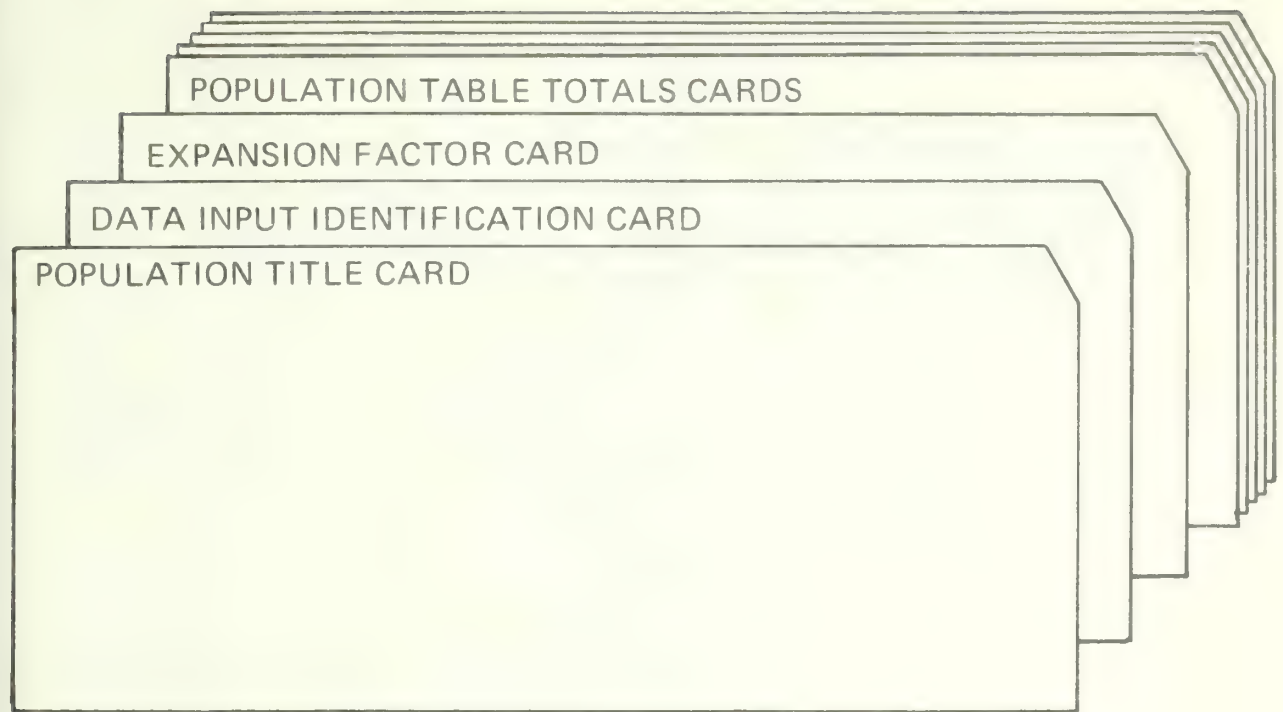


Figure 19.--Order of population description cards in the Job Control Deck. A set of cards like this must be available for each population in a job using processing option 6. With other processing options, the last set of cards is not used.

POPULATION TITLE CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-80	AAA...A	80 alphameric characters, giving a descriptive title for a population. This title is printed at the top of every page of output.

DATA INPUT IDENTIFICATION CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-11	INPUTbIDENT	Card label.
12	b	
13-20	XXX...X	8 numeric characters, giving the <u>value</u> of the <u>data field</u> appearing first under the data set identification given on the INPUT FIELDS IDENTIFICATION CARD in TABLE-2. The value given here is the initial value; that is, it is the value appearing with the first set of tables for the population.
21-52	XXX...X	Repetition of format of columns 13-20 or the <u>initial values</u> of the remaining <u>data fields</u> specified in the data set identification.

EXPANSION FACTOR CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-12	EXPANbFACTOR	Card label.
13	b	
14-28	bX.XXXXXXXXXXEbXX	A 15-character numeric field (E specification), giving the value of the expansion factor (normally the size of the population that has been sampled, such as area of a forest district) by which every cell of every output table for the population will be multiplied. This value is referred to by the symbol "wt" in the summary of estimating procedures.

29	b	
30-32	XXX	3 numeric characters, giving the number of sampling strata in the population. The number must be <u>right-justified</u> in the field. If the sampling option given in column 15 of the JOB CONTROL CARD is 1 or 2, this field must contain 1.
33	b	
34-48	bX.XXXXXXXXXXebXX	A 15-character numeric field (E specification), giving the sum of the sample weights. If the sampling option given in column 15 of the JOB CONTROL CARD is 1 or 2, this value must be 0.00000000E 00. This value is referred to by the symbol "n" in the summary of estimating procedures.

POPULATION TABLE TOTALS CARD(S) (Optional)

This set of cards is used only when processing option 6 is specified in column 15 of the JOB CONTROL CARD.

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-12	TABLEbTOTALS	Card label
13	b	
14-28	bX.XXXXXXXXXXebXX	A 15-character numeric field (E specification), giving the mean value for a population of the grand total cell of an output table. This value is referred to by the symbol "t" in the summary of estimating procedures.
29	b	
30-44	bX.XXXXXXXXXXebXX	A 15-character numeric field (E specification), giving the variance of the mean value in columns 14-28. This value is referred to by the symbol "vt..." in the summary of estimating procedures.

6. Sample Description Cards

The control cards described in this section appear in the Job Control Deck only if the information they contain--sample weights, and independent estimates of the sample means and variances of the grand total cell of each output table--is required by the processing option being used. If these cards are required, they must appear as a set following each set of population description cards. The arrangement of the individual cards in the group is shown in figure 20.

The SAMPLE WEIGHT CARD is not used when processing option 1 or 2 is specified in column 15 of the JOB CONTROL CARD. Otherwise, there must be one card of this type for each sample in a given population. Each card contains the weight by which sample values will be multiplied before summing to population values. It also contains a second weight that may be used when estimates for a segment of the population are being made. The order of these cards in the set must be the same as that of the sample summaries in the data input file.

The SAMPLE TABLE TOTALS CARD(S) is used only when processing option 5 is specified in column 15 of the JOB CONTROL CARD. It contains the independent estimates of sample (or stratum) mean and variance for one output table. There must be as many of these cards in the set for a sample as there are output tables, and they must be ordered in the set according to the order listed on the TABLE SELECTION CARD. The set for each sample immediately follows the corresponding SAMPLE WEIGHT CARD for that sample.

SAMPLE WEIGHT CARDS (Optional)

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-12	STRATUMBWTS.	Card label.
13	b	
14-28	bX.XXXXXXXXXXebXX	A 15-character numeric field (E specification), giving the value of the weight to be applied to the data for a sampling stratum. This value is referred to by the symbol " n_j " in the summary of estimating procedures.

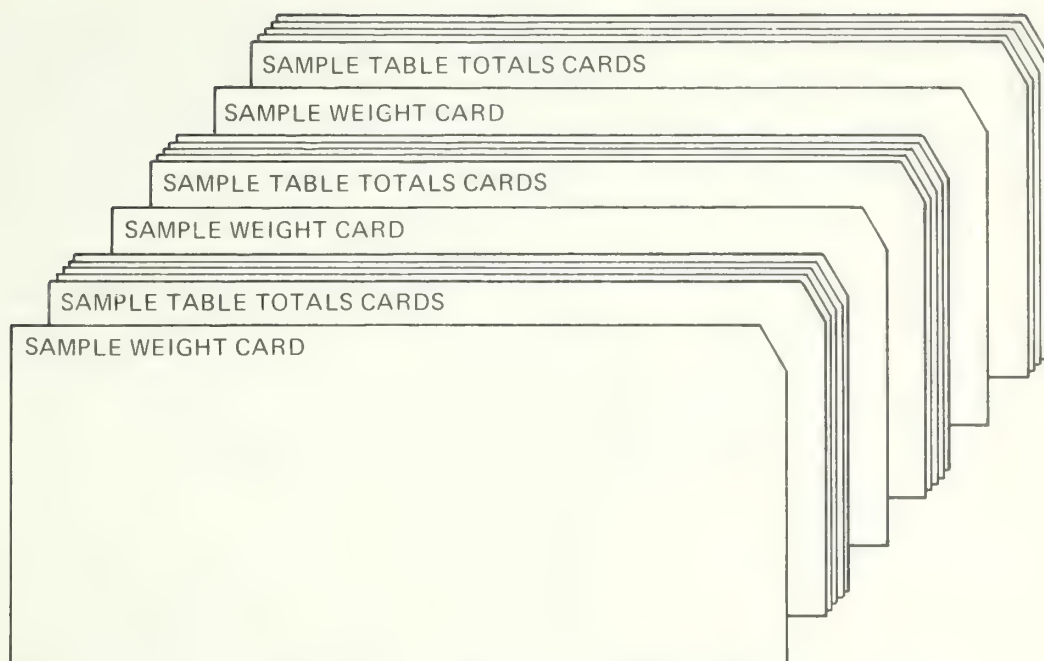


Figure 20.--Order of sample description cards in the Job Control Deck.
The setup for a population with three samples, using
processing option 5, is illustrated.

29	b	
30-44	bX.XXXXXXXXXXEbXX	A 15-character numeric field (E specification), giving the value of the adjustment factor to be applied to the variances for a sampling stratum when compiling estimates for a fraction of the population. This value is referred to by the symbol " n/n_j " in the summary of estimating procedures. If the value is 0.00000000Eb00, it indicates that estimates for the population as a whole are being compiled, so the adjustment factor will not be applied.

SAMPLE TABLE TOTALS CARDS (Optional)

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-12	TABLEbTOTALS	Card label.
13	b	
14-28	bX.XXXXXXXXXXEbXX	A 15-character numeric field (E specification), giving the mean value for a sampling stratum of the grand total cell of an output table. This value is referred to by the symbol " \bar{t}_j " in the summary of estimating procedures.
29	b	
30-44	bX.XXXXXXXXXXEbXX	A 15-character numeric field (E specification), giving the variance of the mean value in columns 14-28. This value is referred to by the symbol " $v\bar{t}_j$ " in the summary of estimating procedures.

UPDATE TABLE CARDS

If update tables have been punched using options 3 or 4 of the TABLE SELECTION CARD, they must be added to the control cards at this point if options 2 or 4 are specified.

7. Population Group Title Card

This card is used in the Job Control Deck only if sums over all populations in the job (see Job Control Card, column 13) are required as output. It gives a descriptive title for the group of populations represented by these sums. The title is printed at the top of every page of the "sums" output. If used, the card is placed in the Job Control Deck following all other control cards for a given job.

POPULATION GROUP TITLE CARD (Optional)

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-80	AAA...A	80 alphameric characters, giving a descriptive title for the tables of sums over populations in the group.

END OF RUN CARD

<u>Columns</u>	<u>Contain</u>	<u>Explanation</u>
1-3	END	A control word, signifying the end of the Job Control Deck. This card must always be the last card in the Job Control Deck to show that there are no more jobs to be processed.

B. OUTPUT-2 OPERATION

The use of OUTPUT-2 to obtain population statistics by processing sample summary data is covered in the information given below. To facilitate checking the setup of processing runs, some of the information given is a resume of material covered elsewhere.

1. Program Restrictions

The program carries limitations on the overall size and on certain dimensions of processing problems that can be handled in a single processing run. They are:

a. The total number of summary tables for a given sample in the data input file cannot exceed 40.

b. The total number of storage locations available to produce output tables of statistics for a given population is 40,000. The limitations on the numbers of cells in all output tables for the population is more stringent and depends on the processing option being used. (See formula on page 62.)

- c. The number of rows in an individual output table cannot exceed 201.
- d. The number of columns in an individual output table cannot exceed 100.
- e. The number of ratio tables cannot exceed 50.
- f. The number of table label sets defined under the repeat labels specification of table labels cannot exceed 150.

These restrictions result primarily from the way in which the available storage capacity of the computer has been allocated to various uses in the program. However, the program has been constructed so that the more important of these allocations can readily be changed if a problem of substantially different relative dimensions is encountered.

2. Job Control Deck Setup

The Job Control Deck consists of all the punched cards through which processing specifications, necessary constants, and other data (exclusive of the data to be processed) are entered into the computer. These cards, and the logical groups into which they fall, have been described in the previous section. The assembly of the groups of control cards to form the Job Control Deck, as well as the placement of the Job Control Deck in the monitor input deck, are shown in figure 21.

It should be noted that the monitor input deck consists of the program deck, followed by the Job Control Deck, with system control cards interspersed. The latter cannot be described in detail here because they vary from one computer installation to another. For more information about them, see the systems representative at the computer center where the processing will be done.

3. Input Data Setup

The normal data input is a magnetic tape file written in the binary mode and containing all the tables of sample statistics to be processed in a given run. The tables will be grouped in known order (see the order of the OUTPUT TABLE DEFINITION CARDS in the Job Control Deck for TABLE-2) within each sample, and the samples will be grouped in known order (see the order of the data sets in the data input file to TABLE-2) within the population. Because the input data file is searched for the proper data each time a population is to be processed, the population data may be in any order and the file may also contain extraneous data which will be skipped in processing. However, all data to be processed must be contained in a single file. If it is in multiple files, it must be processed in multiple passes.

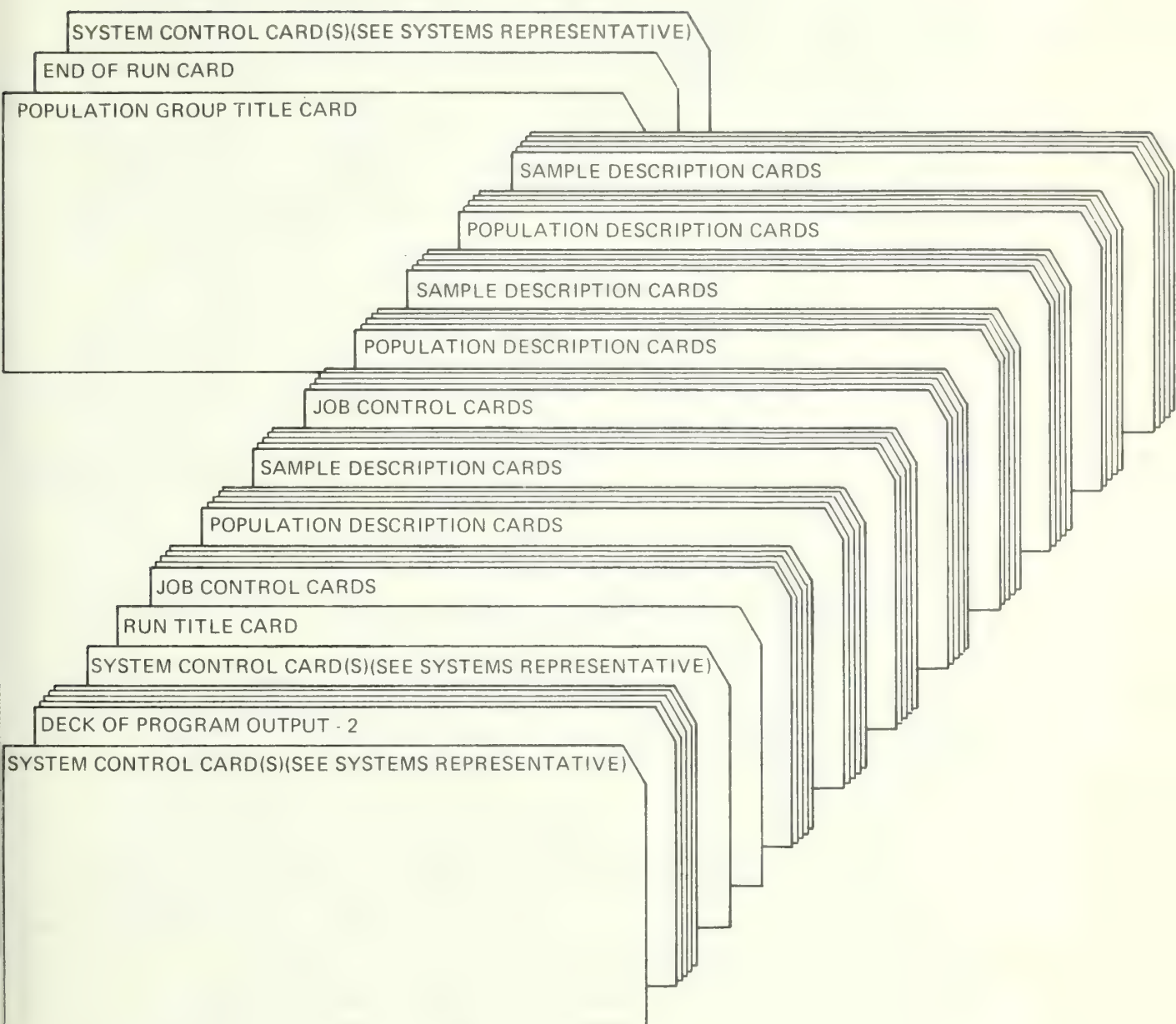


Figure 21.--The Job Control Deck setup, illustrating the kinds of cards that are necessary and the order in which they must be arranged. The example is for a run that contains two jobs, the first requiring statistics for one population, and the second requiring statistics for two populations and the sum of the two groups.

In addition to these requirements, the input data must have been produced in TABLE-2 under an output option that is consistent with the processing option to be used in OUTPUT-2. The necessary relationships are:

<u>OUTPUT-2 proc- essing option</u>	<u>TABLE-2 output option</u>	<u>Sample summary table contains</u>
1	1 or 2	Sample sums or means.
2	3 or 5	Sample means and their variances.
3	3 or 5	Sample means and their variances.
4	3 or 5	Sample means and their variances
5	4	Sample means, their variances, and covariances of individual means with grand means with- in the table.
6	4	Sample means their variances, and covariances of individual means with grand means with- in the table.

4. Messages Printed During Execution

The messages listed below are those printed by the program during execution.

Other messages also may appear in the printed summary of the run. They will be produced by the operating system under which this program is being executed. For the meaning and consequences of any message not found in the list below, see your computer systems representative.

MAIN Messages

1. THE JOB CONTROL CARD IS INCORRECT.

The message prints if JOB is not punched in the first three columns of the card or if any of the coded options are incorrect.

2. THE TABLE SELECT CARD IS INCORRECT.

The first six columns of the card must contain the word, TABLES.

3. THE TABLE SCALE FACTOR CARD IS INCORRECT.

The first six columns of the card must contain the word, SCALES.

4. AN INPUT IDENTIFICATION CARD IS INCORRECT.

The first 12 columns of the card must contain the words, INPUT IDENT.

5. AN EXPANSION FACTOR CARD IS INCORRECT.

The first 12 columns of the card must contain the words, EXPAN FACTOR, and the value of the expansion factor must be greater than zero.

6. A POPULATION TABLE TOTALS CARD IS INCORRECT.

The first 12 columns of the card must contain the words, TABLE TOTALS. This card is needed when using sampling option 4.

7. A STRATUM WEIGHTS CARD IS INCORRECT.

The first 12 columns of the card must contain the words, STRATUM WTS.

8. A STRATUM TABLE TOTALS CARD IS INCORRECT.

The first 12 columns of the card must contain the words, TABLE TOTALS. This card is needed when using sampling option 5.

SUBR2 Message

9. DIMENSIONED SPACE OF XXXXXX HAS BEEN EXCEEDED. INCREASE THE DIMENSION OF ARRAY XIMP TO XXXXXX OR REDUCE THE SIZE AND/OR NUMBER OF TABLES.

The total storage requirement needed to produce the desired output table set has exceeded the dimensioned value.

SUBR5 Message

10. THE TABLE NAMED AAAA HAS ITS LABELS MISSING OR OUT OF ORDER.

The table name on the TABLE TITLE CARD does not correspond with a table name on the input file. The table is missing from the deck or has been bypassed when searching for previous tables.

SUBR8 Messages

11. RATIO TABLES END CARD MISSING - OR - ATTEMPT TO DEFINE MORE THAN XXX RATIO TABLES. INCREASE DIMENSION LRMAX IF NECESSARY

The RATIO TABLE DEFINITION CARDS must be terminated by an END OF RATIO TABLES CARD.

12. TABLE NAMED AAAA CANNOT BE FOUND FOR RATIO TABLE.
AAAA=AAAA/AAAA.

The dividend or divisor table name is misspelled or the table was not selected on the TABLE SELECT CARD.

13. TABLES AAAA AND AAAA DO NOT HAVE THE SAME DIMENSIONS TO COMPUTE RATIO TABLE AAAA=AAAA/AAAA.

The dividend and divisor tables must have the same number of rows and columns.

LABELS Messages

14. SUBROUTINE LABELS CAN ONLY HANDLE XXXX TABLE LABEL SETS.

Variable MAXSET in SUBROUTINE LABELS must be increased.

15. THE NAME AAAA HAS ALREADY BEEN USED FOR SET NUMBER XXXX.

Each table label set must have a unique name.

16. NOT ENOUGH ROOM TO STORE TABLE LABEL SET NUMBER XXXX
NAME=AAAA.

Increase dimension LTOTAL or reduce the number of label sets.

17. TABLE LABEL SET AAAA HAS NOT BEEN DEFINED.

A TABLE LABEL SET REFERENCE CARD named a set that was not defined by any TABLE LABEL SET DEFINITION CARD.

C. OUTPUT-2 MODIFICATION OF DIMENSIONED SPACE

OUTPUT-2 carries restrictions on both the dimensions and the overall size of problem that can be handled in a single-processing run. These restrictions are a result of the manner in which dimensioned space has been allocated (table 2) and the total space available in a given operating system. The program has been written so that all modifications of dimensioned space can be made in the main program called OUTPUT. No other parts of the program need be touched for this purpose. The use of dimensioned space and the means of changing dimensions are discussed in detail in the following section.

Table 2.--*Summary of dimensioned space restrictions, and associated program variables and arrays*

Item	Restriction	Variable	Arrays
Maximum number of input tables	40	LOUT	LTABLE, ITAB, TOTAL, TOTVAR, LENGTH
Maximum number of locations available for compilation of output tables	40,000	LTOTAL	XIMP
Maximum number of rows per table	201	NRMAX	RHEAD, LEXTRA
Maximum number of columns per table	101	NCMAX	CHEAD
Maximum number of ratio tables	50	LRMAX	LRATIO
Maximum number of label sets	150	MAXSET (Used only in subroutine LABELS)	Not applicable

1. Number of Input Tables

In OUTPUT-2, up to 40 input tables per data set may be contained in the input data. This is consistent with the number that may be specified in the Job Control Deck for TABLE-2. To change this maximum, the following steps (and only these) must be taken:

a. In the program called OUTPUT, the variable named LOUT must be set equal to the desired maximum value.

b. In the program called OUTPUT, the DIMENSION statement must be changed so that the first dimension of the array ITAB equals the new value of LOUT.

c. In the program called OUTPUT, the DIMENSION statement must be changed so that the dimension of the arrays LTABLE, LSUB2, LSCALE, ITAB, TOTAL, and TOTVAR equals the new value of LOUT.

2. Number of Cells in All Output Tables

In the OUTPUT-2 up to 40,000 locations are available for compiling output tables. To change this maximum, the following steps (and only these) must be taken:

a. In the program called OUTPUT, the variable named LTOTAL must be set equal to the desired maximum value.

b. In the program called OUTPUT, the DIMENSION statement must be changed so that the dimension of the array XIMP equals the new value of LTOTAL.

If the space required for compilation of the output tables specified in the output table selection card exceeds the dimensioned space, a message will be printed during the reading of the Job Control Deck and processing will halt. The space required can be computed as follows:

$$K \sum_{i=1}^n r_i c_i + M \quad \text{where } M = 0 \text{ for options 1,3,4,5,6} \\ M = \text{maximum } (r_i c_i) \text{ for option 2}$$

Sampling option	Values of K			
	Totals only, No sums	Totals only, Sums	Totals+, ¹ No sums	Totals+, ¹ Sums
1	2	3	2	3
2	1	2	2	4
3	2	3	4	6
4	2	3	4	6
5	2	3	6	8
6	2	3	6	8

¹Totals+ meaning that variances or standard error tables also are called for.

- n = The total number of output tables requested in the output table selection card.
- r_i = The number of rows in the i th output table, including a row of column totals if produced.
- c_i = The number of columns in the i th output table, including a column of row totals if produced.

D. OUTPUT-2 PROGRAMING FEATURES

1. File Assignments

<u>Unit</u>	<u>Use</u>
LU1 = 1	File for output of final tables in BCD (LU1 = 10 for Fort Collins version)
LU2 = 2	File for binary input from program TABLE
LU3 = 3	Scratch file for temporary storage of table titles and labels
LU5 = 5	Monitor card reader
LU6 = 6	Monitor line printer
LU7 = 7	Monitor card punch for punching update tables

These logical unit assignments can be changed to fit local conditions by changing the assignments in the main calling program titled OUTPUT.

2. Subprogram Names and Functions

<u>Name</u>	<u>Function</u>
OUTPUT	The main program of the OUTPUT-2.
MAIN	Reads Job Control Decks and calls other subprograms used to compile final output tables. Called from OUTPUT.
SUBR1	Reads a set of stratum tables from unit LU2. Called from MAIN.
SUBR2	Computes storage addresses in array XIMP for all tables and stores the addresses in ITAB and stores number of cells in each table in array LSUB2. Called from MAIN.
SUBR3	Stores the stratum tables in array XIMP. Called from MAIN.
SUBR4	Computes final values for population tables and sums over populations. Called from MAIN.

SUBR5	Reads table titles and labels from unit LU3. Called from MAIN.
SUBR6	Writes the final output tables. Called from MAIN and SUBR8.
SUBR7	Calculates standard errors as percentages of corresponding totals. Called from MAIN.
SUBR8	Reads, decodes, and computes ratio tables. Called from MAIN and SUBR2.
LABELS	Reads the table labels from unit LU5 and writes them on unit LU3. Called from MAIN.
COMMAS	Composes and writes COMMA format output table entries. Called from SUBR6.

3. Important Arrays and Variables

<u>Array</u>	<u>Dimension</u>	<u>Description</u>
LTOTAL	1	The number of storage locations reserved for storage of output tables.
XIMP	LTOTAL	Storage for all output tables.
LOUT	1	The maximum number of input tables for a sampling unit.
LTABLE	LOUT	Storage for information read from the TABLE SELECTION CARD in the Job Control Deck.
LSUB2 (LENGTH in SUB2)	LOUT	A storage array to store the number of cells (rows by columns including subtotals) in each output table.
LSCALE	LOUT	Storage for table scale factors read from the TABLE SCALE FACTOR CARD(S) in the Job Control Deck.
TOTAL	LOUT	Storage for estimates of table totals supplied in the Job Control Deck.
TOTVAR	LOUT	Storage for estimates of variances of table totals (supplied in the Job Control Deck).

ITAB	LOUT,13	Indexing information for array XIMP, where the second dimension locations are used as follows: 1 = The number of rows in the i th input table. 2 = The number of columns in the i th input table. 3 = The name of the i th input table. 4 = The beginning location in XIMP of the means for the i th input table. 5 = The beginning location in XIMP of the variances for the i th input table. 6 = The beginning location in XIMP of the co-variances for the i th input table. 7 = The beginning location in XIMP of the temporary storage for the calculation of final means for the i th input table. 8 = The beginning location in XIMP of the temporary storage for the calculation of final variances for the i th input table. 9 = The beginning location in XIMP of the temporary storage for the calculation of final covariances for the i th input table. 10 = The beginning location in XIMP of the population group sums for the i th input table. 11 = The beginning location in XIMP of the population group variances for the i th input table. 12 = The location in the XIMP temporary storage for calculation of the total for the i th input table. 13 = The location in the XIMP temporary storage for calculation of the variance of the total for the i th input table.
LRATIO	LRMAX,5	1 = Ratio table name 2 = Dividend table name 3 = Divisor table name 4 = Dividend table number 5 = Divisor table number
IDENT	6	Storage for data set identification fields read from the Job Control Deck.
IDNOW	6	Storage for data set identification fields read from binary input tape.

CHEAD	NCMAX,5	Storage array for the column headings of an output table. Space is provided for a heading of five alphameric words (second dimension) for a total of 20 characters for each of up to 101 columns, including row totals (if row totals were produced in TABLE-2).
RHEAD	NRMAX,5	Storage array for the row headings of an output table. Space is provided for a heading of five alphameric words (second dimension) for a total of 20 characters for each of up to 101 rows, including column totals (if column totals were produced in TABLE-2).
LEXTRA	NRMAX	Working storage for row label line skip control.
TITLE	20	Working storage for titles of populations, population groups, and tables.
TAB	39	Working storage for table titles.
ST	20	Working storage for description of type of table produced (totals, variances, etc.).
ISUPRS	80	Storage for population suppression read from the Job Control Deck.
XHTOT	4	Estimated totals heading text.
XHVAR	8	Variance heading text.
XHSE	7	Standard errors heading text.
XHSEP	16	Standard errors as percentages heading text.
X	5	Working storage for update tables.
NTABLE	1	Number of tables read from data input for a data set ($NTABLE \leq LOUT$).
WT	1	Stratum weight, read from Job Control Deck.

SUMWTS	1	Sum of stratum weights for a population, read from Job Control Deck.
FACTOR	1	Population expansion factor, read from Job Control Deck.
NSTRAT	1	Number of strata to be processed for a population, read from Job Control Deck.
ADJUST	1	Adjustment factor for a stratum, read from Job Control Deck.
NOPT	1	Sampling option ($1 \leq \text{NOPT} \leq 6$).
NLIST	1	Job Control Deck listing option. 0 = No listing. 1 = Entire Job Control Deck. 2 = Job Control Deck with exception of table titles and row and column labels.
NJOB	1	Number of populations to be processed in the current job.
NOUT	1	Output option for final tables. 0 = Tape output. 1 = Printer output.
NSUM	1	Option for population group sums. 0 = No sums. 1 = Produce sums for population groups. 2 = Suppress all populations. 3 = Read population suppression control card.
IFMT	1	Output format option. 0 = E format. 1 = F format. 2 = Commas format.
NTOT	1	Option for output of totals. 0 = No output of totals. 1 = Produce tables of totals.
NVAR	1	Option for output of variances. 0 = No output of variances. 1 = Produce tables of variances.

NSE	1	Option for output for standard errors. 0 = No output of standard errors. 1 = Produce tables of standard errors.
NSEP	1	Option for output of standard errors as percentages. 0 = No output of standard errors as percentages. 1 = Produce tables of standard errors as percentages.
NOSE	1	Number of standard errors at which percentages are to be expressed.
NTLE	1	Number of title cards for each table. 0, 1 = 1 TABLE TITLE CARD. 2 = 2 TABLE TITLE CARD.
MTLE	1	Option to print table name. 0 = Do not print table name. 1 = Print table name.
NSCL	1	Option for TABLE SCALE FACTOR CARD. 0 = No TABLE SCALE FACTOR CARD(S). 1 = Read TABLE SCALE FACTOR CARD(S).
NRSP	1	Option for row spacing. 0, 1 = Single space. 2 = Double space.
IDIV	1	Option for ratio tables. 0 = No ratio tables. 1 = Read the list of ratio tables.
NDIVS	1	Counter for number of ratio tables.
NAME	1	Name of an output table punched in columns 1-4 of TABLE TITLE CARD.

E. OUTPUT-2 SUMMARY OF ESTIMATING PROCEDURES

In this section the six processing options available in program OUTPUT are presented in detail.

Vector notation is used to make the presentation of computing procedures more compact and easier to read. An input vector, Y^I , is a one-dimensional array representing a sampling unit attribute. An output vector, Y^O , represents an output table (in general, a two-dimensional array or matrix) summarizing the sampling unit attribute. A final output vector, Y^F , represents an estimate of the population attribute corresponding to the sampling unit attribute. Elements of these vectors are represented by y^I_i , y^O_i , or y^F_i .

It must not be inferred from what follows that the arithmetic is the arithmetic of vectors or matrices; though, in general, it is correct vector arithmetic as shown. What is implied is simply the sequential and independent application of the indicated operation to each pair of equivalent elements from the two vectors. In this sense, the procedures will generalize to the case of matrices; otherwise, they will not.

Other notational conventions adopted here are the use of a bar over an attribute symbol (\bar{Y}) to symbolize the arithmetic mean of an attribute; and the use of a dot replacing a subscript ($Y_{.jk}$) to indicate the sum over all members of the set represented by the subscript.

OPTION 1.--Process as a 100-percent Sample of the Population

Compute: $Y^F_{..}$

Given: Sets of $Y^O_{j.}$; and n_s

Where:

j = Subscript for the j th set of sampling units

k = Subscript for the k th sampling unit

$Y^F_{..}$ = A final attribute vector (output table) for a survey unit, containing the sum over the entire population of sampling units of the sampling unit attribute vectors, Y^O_{jk}

$Y_{j\cdot}^0$ = An attribute vector (output table) that contains the sum over a set of sampling units of the sampling unit attribute vectors, Y_{jk}^0 , which represent a summary of a sampling unit attribute input vector

ns = The number of sets of sampling units

Procedure: None.

Output:

$$Y_{\cdot\cdot}^F = \sum_{j=1}^{ns} Y_{j\cdot}^0$$

OPTION 2.--Process as a Single Random Sample of the Population

Compute: $Y_{\cdot\cdot}^F$, $VY_{\cdot\cdot}^F$, $STY_{\cdot\cdot}^F$, and $SEY_{\cdot\cdot}^F$,

Given: $\bar{Y}_{\cdot\cdot}^0$, $V\bar{Y}_{\cdot\cdot}^0$, and wt

Where:

j = Subscript for the j th sample stratum or set of sampling units; hence, not applicable in this case of a single set in the survey unit

k = Subscript for the k th sampling unit

$Y_{\cdot\cdot}^F$ = A final attribute vector (output table) for a survey unit, containing an estimate of the sum over the entire population of sampling units of the sampling unit attribute vectors, Y_{jk}^0

$VY_{\cdot\cdot}^F$ = The variance of $Y_{\cdot\cdot}^F$

$STY_{\cdot\cdot}^F$ = The standard error of $Y_{\cdot\cdot}^F$

$SEY_{\cdot\cdot}^F$ = The sampling error (in percent) of $Y_{\cdot\cdot}^F$

$\bar{Y}_{\cdot\cdot}^0$ = An attribute vector (output table) that contains the arithmetic mean of the sampling unit attribute vectors, Y_{jk}^0 , which represent a summary of a sampling unit attribute input vector

$\overset{0}{V\bar{Y}}_{..}$ = The variance of $\overset{0}{\bar{Y}}_{..}$

wt = The total number of sampling units in a survey unit population

Output: $\overset{F}{Y}_{..} = \overset{0}{\bar{Y}}_{..} \text{ wt}$

$\overset{F}{VY}_{..} = \overset{0}{V\bar{Y}}_{..} \text{ wt}^2$

$\overset{F}{STY}_{..} = \sqrt{\overset{F}{VY}_{..}}$

$\overset{F}{SEY}_{..} = \frac{\overset{F}{STY}_{..}}{\overset{F}{Y}_{..}} 100$

OPTION 3.--Process as Random Samples from Known Population Strata

Compute: $\overset{F}{Y}_{..}$, $\overset{F}{VY}_{..}$, $\overset{F}{STY}_{..}$, and $\overset{F}{SEY}_{..}$

Given: Sets of $\overset{0}{\bar{Y}}_{j\cdot}$, $\overset{0}{V\bar{Y}}_{j\cdot}$, n_j ; and ns, wt

Where:

j = Subscript for the j th sample stratum or set of sampling units

k = Subscript for the k th sampling unit

$\overset{F}{Y}_{..}$ = A final attribute vector (output table) for a survey unit, containing an estimate of the sum over the entire population of sampling units of the sampling unit attribute vectors, $\overset{0}{Y}_{jk}$

$\overset{F}{VY}_{..}$ = The variance of $\overset{F}{Y}_{..}$

$\overset{F}{STY}_{..}$ = The standard error of $\overset{F}{Y}_{..}$

$\overset{F}{SEY}_{..}$ = The sampling error (in percent) of $\overset{F}{Y}_{..}$

$\bar{Y}_{j.}^0$ = An attribute vector (output table) that contains the arithmetic mean for a stratum of the sampling unit attribute vectors, \bar{Y}_{jk}^0 , which represent a summary of a sampling unit attribute input vector

$V\bar{Y}_{j.}^0$ = The variance of $\bar{Y}_{j.}^0$.

n_j = The known size of stratum or weight to be applied to the stratum

ns = The number of sample strata in a survey unit

wt = The total number of sampling units in a survey unit population

Procedure:
$$\bar{Y}_{..}^F = \frac{1}{n.} \sum_{j=1}^{ns} n_j \bar{Y}_{j.}^0$$

$$V\bar{Y}_{..}^F = \frac{1}{n.^2} \sum_{j=1}^{ns} n_j^2 V\bar{Y}_{j.}^0$$

Output:
$$\bar{Y}_{..}^F = \bar{Y}_{..}^F \text{ wt}$$

$$V\bar{Y}_{..}^F = V\bar{Y}_{..}^F \text{ wt}^2$$

$$STY_{..}^F = \sqrt{\frac{F}{V\bar{Y}_{..}^F}}$$

$$SEY_{..}^F = \frac{STY_{..}^F}{\bar{Y}_{..}^F} 100$$

OPTION 4.--Process as Random Samples from Population Strata
Estimated from a Primary Random Sample

Compute: $\bar{Y}_{..}^F$, $V\bar{Y}_{..}^F$, $STY_{..}^F$, and $SEY_{..}^F$.

(Note: Procedure assumes that samples are not a subset of the primary sample. If samples are a subset, the value of $V\bar{Y}_{..}^F$ will be slightly higher than the variance would be from a modified formula.)

Given: Sets of $\bar{Y}_{j.}^0$, $V\bar{Y}_{j.}^0$, n_j ; and ns, wt

Where:

j = Subscript for the j th sample stratum or set of sampling units

- k = Subscript for the k th sampling unit
- F
 $Y_{..}$ = A final attribute vector (output table) for a survey unit, containing an estimate of the sum over the entire population of sampling units of the sampling unit attribute vectors, $\overset{0}{Y}_{jk}$
- F
 $VY_{..}$ = The variance of $Y_{..}$
- F
 $STY_{..}$ = The standard error of $Y_{..}$
- F
 $SEY_{..}$ = The sampling error (in percent) of $Y_{..}$
- $\overset{0}{Y}_{j.}$ = An attribute vector (output table) that contains the arithmetic mean for a stratum of the sampling unit attribute vectors, $\overset{0}{Y}_{jk}$, which represent a summary of a sampling unit attribute input vector.
- $\overset{0}{VY}_{j.}$ = The variance of $\overset{0}{Y}_{j.}$
- n_j = The number of sampling units in the first (photo) sample of a sample stratum
- ns = The number of sample strata in a survey unit
- wt = The total number of sampling units in a survey unit population

Procedure:
$$\overset{F}{Y}_{..} = \frac{1}{n.} \sum_{j=1}^{ns} n_j \overset{0}{Y}_{j.}$$

$$\overset{F}{VY}_{..} = \left[\frac{1}{n.^2 - n.} \sum_{j=1}^{ns} [(n_j^2 - n_j) \overset{0}{VY}_{j.} + n_j \overset{0}{Y}_{j.}^2] \right] - \left[\frac{1.0}{n. - 1} \overset{F}{Y}_{..}^2 \right]$$

Output:
$$\overset{F}{Y}_{..} = \overset{F}{Y}_{..} wt$$

$$\overset{F}{VY}_{..} = \overset{F}{VY}_{..} wt^2$$

$${}^F\text{STY}_{..} = \sqrt{{}^F\text{VY}_{..}}$$

$${}^F\text{SEY}_{..} = \frac{{}^F\text{STY}_{..}}{{}^F\text{Y}_{..}} 100$$

OPTION 5.--OPTION 4 Modified to Obtain Stratum Ratios for Application to Independent Estimates of Stratum Means and Variances

Compute: ${}^F\text{Y}_{..}$, ${}^F\text{VY}_{..}$, ${}^F\text{STY}_{..}$, and ${}^F\text{SEY}_{..}$.

Given: Sets of $\bar{Y}_{j.}^0$, $\text{V}\bar{Y}_{j.}^0$, $\text{C}\bar{V}_{j.}^0$, $\bar{t}_{.j.}$, $v\bar{t}_{.j.}$, n_j ; and ns, wt

Where:

i = Subscript for the i th element of a vector
 j = Subscript for the j th sample stratum or set of sampling units

k = Subscript for the k th sampling unit

${}^F\text{Y}_{..}$ = A final attribute vector (output table) for a survey unit, containing an estimate of the sum over the entire population of sampling units of the sampling unit attribute vectors \bar{Y}_{jk}^0

${}^F\text{VY}_{..}$ = The variance of ${}^F\text{Y}_{..}$

${}^F\text{STY}_{..}$ = The standard error of ${}^F\text{Y}_{..}$

${}^F\text{SEY}_{..}$ = The sampling error (in percent) of ${}^F\text{Y}_{..}$

$\bar{Y}_{j.}^0$ = An attribute vector (output table) that contains the arithmetic mean for a stratum of the sampling unit attribute vectors, \bar{Y}_{jk}^0 , which represent a summary of a sampling unit attribute input vector.

$\text{V}\bar{Y}_{j.}^0$ = The variance of $\bar{Y}_{j.}^0$

$\frac{0}{CV}_{j.}$ = The mean covariance for a stratum of sampling unit attribute vectors, $\overset{0}{Y}_{jk}$, and the sums (totals) of elements in these vectors, $\overset{0}{y}_{.jk}$

$\bar{t}_{.j.}$ = An independent estimate of $\overset{0}{y}_{.j.}$, the arithmetic mean over the entire population of sampling units in a sample stratum, of the sums of the elements of the sampling unit attribute vectors, $\overset{0}{Y}_{jk}$

$vt_{.j.}$ = The variance of $t_{.j.}$

n_j = The number of sampling units in the first (photo) sample of a sample stratum

ns = The number of sample strata in a survey unit population

wt = The total number of sampling units in a survey unit population

Procedure:

$$R_{j.} = \frac{\frac{0}{Y}_{j.}}{\frac{0}{y}_{.j.}} ; \quad \frac{F}{Y}_{j.} = R_{j.} \bar{t}_{.j.} ; \quad \frac{F}{Y}_{..} = \frac{1}{n.} \sum_{j=1}^{ns} n_j \frac{F}{Y}_{j.}$$

$$VR_{j.} = R^2_{j.} \left[\frac{\frac{0}{VY}_{j.}}{\frac{0}{Y^2}_{j.}} + \frac{\frac{0}{vy}_{.j.}}{\frac{0}{y^2}_{.j.}} - 2 \frac{\frac{0}{CV}_{j.}}{\frac{0}{Y}_{j.} \frac{0}{y}_{.j.}} \right]$$

$$\frac{F}{VY}_{j.} = \frac{F}{Y^2}_{j.} \left[\frac{VR_{j.}}{R^2_{j.}} + \frac{vt_{.j.}}{\bar{t}^2_{j.}} \right]$$

$$\frac{F}{VY}_{..} = \left[\frac{1}{n^2. - n.} \sum_{j=1}^{ns} [(n^2_j - n_j) \frac{F}{VY}_j + n_j \frac{F}{Y^2}_{j.}] \right] - \left[\frac{1.0}{n. - 1} \frac{F}{Y^2}_{..} \right]$$

Output:
$$Y_{..}^F = \bar{Y}_{..}^F \text{ wt}$$

$$VY_{..}^F = V\bar{Y}_{..}^F \text{ wt}^2$$

$$STY_{..}^F = \sqrt{\frac{F}{VY_{..}^F}}$$

$$SEY_{..}^F = \frac{STY_{..}^F}{Y_{..}^F} 100$$

OPTION 6.--OPTION 4 Modified to Obtain Population Ratios for Application to Independent Estimates of Population and Variances

Compute: $Y_{..}^F$, $VY_{..}^F$, $STY_{..}^F$, and $SEY_{..}^F$.

Given: Sets of $\bar{Y}_{j\cdot}^0$, $V\bar{Y}_{j\cdot}^0$, $C\bar{V}_{j\cdot}^0$, n_j ; and $\bar{t}_{..}$, $v\bar{t}_{..}$, ns , wt

Where:

i = Subscript for the i th element of a vector

j = Subscript for the j th sample stratum or set of sampling units

k = Subscript for the k th sampling unit

$Y_{..}^F$ = A final attribute vector (output table) for a survey unit, containing an estimate of the sum over the entire population of sampling units of the sampling unit attribute vectors, Y_{jk}^0

$VY_{..}^F$ = The variance of $Y_{..}^F$

$STY_{..}^F$ = The standard error of $Y_{..}^F$

$SEY_{..}^F$ = The sampling error (in percent) of $Y_{..}^F$

$\bar{Y}_{j\cdot}^0$ = An attribute vector (output table) that contains the arithmetic mean for a stratum of the sampling unit attribute vectors, Y_{jk}^0 , which represent a summary of a sampling unit attribute input vector

- $\overset{0}{V\bar{Y}}_{j.}$ = The variance of $\overset{0}{\bar{Y}}_{j.}$
- $\overset{0}{CV}_{j.}$ = The mean covariance for a stratum of sampling unit attribute vectors, $\overset{0}{Y}_{jk}$, and the sums (totals) of elements in these vectors, $\overset{0}{y}_{.jk}$
- n_j = The number of sampling units in the first (photo) sample of a sample stratum
- $\bar{t}...$ = An independent estimate of $\overset{F}{y}...$, the arithmetic mean over the entire population of sampling units, of the sums of the elements of the sampling unit attribute vectors, $\overset{0}{Y}_{jk}$
- $\overline{vt}...$ = The variance of $\bar{t}...$
- ns = The number of sample strata in a survey unit
- wt = The total number of sampling units in a survey unit population

Procedure: $\frac{F}{\bar{Y}..} = \frac{1}{n.} \sum_{j=1}^{ns} n_j \frac{0}{\bar{Y}}_{j.}; \quad R. = \frac{\frac{F}{\bar{Y}..}}{\frac{F}{y...}}$

$$\frac{F}{V\bar{Y}..} = \left[\frac{1}{n^2. - n.} \sum_{j=1}^{ns} [(n_j^2 - n_j) \frac{0}{V\bar{Y}}_{j.} + n_j \frac{0}{\bar{Y}^2}_{j.}] \right] - \left[\frac{1.0}{n. - 1} \frac{F}{\bar{Y}^2..} \right]$$

$$\frac{F}{CV_{..}} = \left[\frac{1}{n^2_{..} - n_{..}} \sum_{j=1}^{ns} [(n^2_{j.} - n_{j.}) \frac{0}{CV_{j.}} + n_{j.} \frac{0}{Y_{j.}} \frac{0}{y_{j.}}] \right] -$$

$$\left[\frac{1.0}{n_{..} - 1} \frac{F}{Y_{..} y_{...}} \right]$$

$$VR_{..} = R^2_{..} \left[\frac{\frac{F}{VY_{..}}}{\frac{F}{Y^2_{..}}} + \frac{\frac{F}{vY_{...}}}{\frac{F}{y^2_{...}}} - 2 \frac{\frac{F}{CV_{..}}}{\frac{F}{Y_{..} y_{...}}} \right]$$

$$\frac{F}{Y_{..}} = R_{..} \bar{t}_{...}$$

$$\frac{F}{VY_{..}} = \frac{F}{Y^2_{..}} \left[\frac{VR_{..}}{R^2_{..}} + \frac{v\bar{t}_{...}}{\bar{t}^2_{...}} \right]$$

Output: $\frac{F}{Y_{..}} = \frac{F}{Y_{..}} wt$

$$\frac{F}{VY_{..}} = \frac{F}{VY_{..}} wt^2$$

$$\frac{F}{STY_{..}} = \sqrt{\frac{F}{VY_{..}}}$$

$$\frac{F}{SEY_{..}} = \frac{\frac{F}{STY_{..}}}{\frac{F}{Y_{..}}} 100$$

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Describes a computer software package for use in devel-
oping statistical tables from a resource inventory data
set. The flexibility of the system in performing user-
designated table-making functions also is described.
Full instructions for operating the system are included.

ODC (100.2)--524.6

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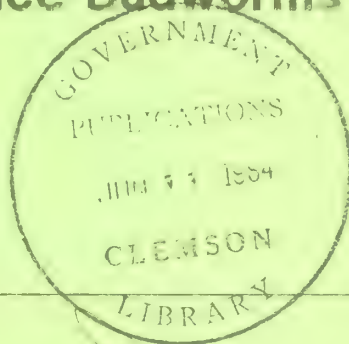
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Proceedings

Forest Defoliator - Host Interactions: A Comparison between Gypsy Moth and Spruce Budworms



FOREWORD

The Canada/U.S. Spruce Budworms Program in cooperation with the Center for Biological Control of Northeastern Forest Insects and Diseases of the Northeastern Forest Experiment Station co-sponsored this Forest Defoliator-Host Interaction Workshop. This invitational workshop was limited to investigators of the spruce budworms and gypsy moth in the Forest Service, Canadian Forestry Service, and the University sector. The primary purpose of this workshop was to foster communication between researchers having a mutual interest and active research projects designed to understand the relationships between the host plant and forest defoliator feeding behavior, growth, and reproduction.

This Workshop was a follow-up to two previous meetings on host-insect interaction. In 1980, Dr. W. Mattson hosted a CANUSA-sponsored meeting at the North Central Forest Experiment Station, St. Paul, MN. This informal gathering brought together CANUSA Program investigators from the US and Canada for the purpose of sharing preliminary information and data on host-insect interactions. The second meeting took place in the fall of 1982. CANUSA(E) sponsored a Symposium on Spruce Budworm-Host Interaction at the Eastern Branch Meeting of the Entomological Society of America, Hartford, CT. The current Workshop developed from this Symposium. We found that participants were raising question concerning the similarity or differences between the spruce budworm and gypsy moth host interaction systems.

These Proceedings resulted from a three-day Workshop held in April 1983 at the Park Plaza Hotel, New Haven, CT. The structure of the Workshop allowed each participant a period for a presentation followed by lengthy discussion. These discussions were lively, friendly technical exchanges clarifying or elaborating on points raised by the speaker. Frequently, these exchanges were thought-provoking and often provided avenues for further detailed discussions and in some cases, future cooperative efforts.

The papers that make up these Proceedings were submitted at the Workshop as camera-ready copy. As a result, the participants did not have the benefit of reappraising their work in light of the discussions that followed their presentations or other ideas that developed at the Workshop.

Since the Workshop was planned late in the life of the CANUSA Program, we asked each investigator to be especially aware of the implications of these interactions on population dynamics of the insect in relation to forest management potential. When possible, we also asked that future research needs and direction be mentioned.

As technical coordinators for this Proceedings, it was our task to arrange and more effectively focus material so that papers provide a smooth transition of ideas and research

activities on insect-host interactions for the spruce budworms and gypsy moth.

Lastly, we would like to acknowledge the support and confidence expressed by the following:

Denver P. Burns, Director, Northeastern Forest Experiment Station

Melvin E. McKnight, Program Leader, CANUSA

William E. Wallner, Director's Representative, Hamden, CT

August 1983

Robert L. Talerico, Broomall, PA

COVER SKETCH

Left, gypsy moth larva; right, spruce budworm larva.

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PROCEEDINGS,

forest defoliator--host interactions:

A comparison between gypsy moth and spruce budworms

New Haven, Connecticut, April 5-7, 1983

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Sponsored jointly by the
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Northeastern Forest Experiment Station

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SUMMARY OF LIFE HISTORY AND HOSTS OF THE

SPRUCE BUDWORMS

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My purpose is to provide background information on the spruce budworms and point out some insect-host interaction relationships that have been noted by others. These and other interactions will be discussed in more detail in the papers that follow.

There are several budworms that feed on forest trees. For our discussions, we will be interested only in the spruce budworm (*Choristoneura fumiferana* Clemens) and the western spruce budworm (*C. occidentalis* Freeman). Other budworms that may be referred to are the 2-year budworm (*C. biennis* Freeman), jack pine budworm (*C. pinus* Freeman) and Modoc budworm (*C. viridis* Freeman). These are all native insects of coniferous forests in North America.

The spruce budworm and western spruce budworm are responsible for significant defoliation in North America. For example in 1982, nearly 24 million hectares or 60 million acres of fir and spruce were visibly defoliated by these insects. There was significant tree mortality at all locations, especially in the East.

I shall briefly review the life history of both budworms to provide a common ground.

Until recently, these species and several near relatives were considered to be strains of *C. fumiferana*. As a result, much early information concerning the western species was published under the name of the spruce budworm. These two budworms have similar life cycles and habits, but differ in geographic range and hosts. I'll use the spruce budworm as an example and note any differences for the western spruce budworm.

Life Cycle and Habits

The spruce budworm has a 1-year life cycle. The rate of development of each stage depends upon climatic factors that vary with geographic regions; thus the following calendar times are only approximate. In the Northeastern United States and Canada, moths lay their eggs

in July. In the West, eggs are laid in July and August. Female budworms lay about 150 eggs in masses of about 20 eggs per mass. Occasionally, egg masses with up to 60 eggs are found. The eggs are light green and are laid in shingle-like fashion, generally on the undersides of needles. Occasionally they appear on the top surface of the needle or overlapping upper and lower surfaces, and at times even on the bark. Egg masses are generally most abundant on shoots in the outer perimeter of the tree crown.

The eggs hatch in about 10 days to 2 weeks. Budworm larvae require six developmental stages or instars from hatching to pupation. Hatching and emergence of first-instar caterpillars are usually complete by mid-August, when one of the two major dispersal periods occurs. Small larvae react photo-positively to light and move upward toward the branch tips. During this activity, some larvae may spin down on silken threads and be carried away by air currents. Such movement or dispersion spreads the larvae over a wide area, but also results in the death of many larvae. Budworm larvae remaining on host foliage do not feed but instead spin cocoon-like shelters (hibernacula) within which they soon molt to the second instar. The budworms overwinter in this stage, preferably on old flower scars on bark scales, or where lichen grows on branches.

In April or May of the following year, second-instar budworms emerge from their hibernacula. Again in response to light, the larvae move toward the branch tips, and the second major airborne redistribution occurs. Again, some larvae drop on silken threads and are blown about by air currents. When these larvae land on suitable host foliage, they begin to feed. Larvae become established in needles of 1-year-old foliage or mine directly into the expanding vegetative buds. Larvae will preferentially eat the more nutritious staminate flowers of balsam fir (*Abies balsamea* (L.) Mill.), when available. Typically, only one balsam fir needle is mined by each larva and the larva molts to the third instar either within the confines of the needle mine or soon after it leaves the needle. By late May or early June, third-instar budworms begin feeding on the newly opened vegetative buds. Larvae feeding on staminate flowers remain in place until the food supply is exhausted; then they move to the new, expanding foliage.

Late-instar (L₄-L₆) budworms are found from early June to early July. A full-grown sixth instar ranges from 0.75 to 1 inch (2 to 2.5 cm) in length. The

body is dark brown with yellowish spots along the back. The head capsule and collar are dark brown or black. The sixth-instar budworm consumes a greater percentage of foliage than any other instar. At sparse population levels, larvae feed only on young needles of current shoots. Sixth-instar budworms normally web two or more shoots together, forming a feeding shelter. When populations reach outbreak levels and all new foliage is consumed, the larvae are forced to feed on old foliage. This phenomenon, called back-feeding, can result in noticeably smaller pupae and smaller egg masses, presumably because older foliage is less nutritious. As foliage is depleted, larval movement increases, and many larvae drop from the defoliated trees to feed on understory host seedlings and young trees.

Pupation occurs within the feeding shelters or other protected locations. A newly formed pupa ranges from 0.5 to 0.75 inches (1.3 to 2 cm) in length and is green when first formed, but becomes yellow. With age the pupa darkens to a dark gray or dark brown. In the East, pupation occurs in late June and lasts from 8 to 12 days. Elevation and aspect, of course, affect these times in the West. In the West, pupae may be found from mid-July to early August.

Moths are present in the field from late June to mid-August. The spruce budworm is usually grayish with dark brown markings and has a wing span of about 0.75 inches (2.0 cm). Color pattern varies: some moths have a more brownish or reddish tinge with the gray markings. The western budworm is slightly larger and has a conspicuous white dot on the outer margin of each forewing. Adults live about 2 weeks, during which time they do not eat. The male locates the female for mating when she releases a sex pheromone. Once mated, females generally do not fly until they have laid at least part of their egg complement. After laying most of their eggs, though, females are active fliers. Given proper weather conditions, both male and female moths may be transported great distances by winds and storm fronts. Such long-range dispersal affects population trends and brings the budworm to new areas.

Hosts

The spruce budworm inhabits the northern coniferous forest of the eastern half of North America. Larvae feed on a number of conifers, but balsam fir, white spruce (Picea glauca (Moench) (Voss), and red spruce (P.

rubens Sarg.) are the major hosts in eastern North America. Black spruce (P. mariana (Mill.) (B.S.P.) is occasionally attacked, as are eastern hemlock (Tsuga canadensis (L.) Carr.), tamarack (Larix laricina (Du Roi) K. Koch), and white pine (Pinus strobus L.).

The forest types of eastern North America differ from west to east. In the Lake States region, balsam fir, white spruce, and black spruce are the major sources of food. These conifers occur in patches that average 15 to 25 acres (6 to 10 ha) and are separated by hardwood or mixed-wood stands. Where hemlock is a common associate, it can be defoliated and more easily killed. In Maine and the Canadian Maritime Provinces, the patchy pattern gives way to extensive areas of softwoods. In this region red spruce becomes a major component of the forest, replacing the white spruce component.

The western spruce budworm is isolated from its eastern sibling species by the mid western prairie that divides the continent. The western spruce budworm causes the greatest economic damage in stands of Douglas-fir (Pseudotsuga Menziesii (Mirb.) Franco), grand fir (Abies grandis (Doug. ex D. Don) (Linde), white fir (A. concolor (Gord. & Glend.) Lendl. ex Hildebr.), subalpine fir (A. lasiocarpa (Hook.) Nutt., blue spruce (Picea pungens Engelm.), Engelman spruce (P. engelmanni Parry ex Engelm.) and white spruce (P. glauca (Moench) Voss). Occasional hosts are corkbark fir (A. lasiocarpa var arizonica (Merriam) Lemm.), Pacific silver fir (A. amabilis Dougl. ex Forbes), Western larch (Larix occidentalis Nutt.), lodgepole pine (Pinus contorta var. latifolia Engelm.), ponderosa pine (P. ponderosa Dougl. ex Laws.), and western white pine (P. monticola Dougl. ex D. Don).

Balsam fir is the most vulnerable host, followed in order by white spruce, red spruce, and black spruce. It takes several years of defoliation to kill a tree. Fir will die after 4 to 7 years of repeated severe defoliations. White and red spruce can withstand at least an additional year or two of complete defoliation before dying. Generally, black spruce is not killed by budworm feeding except in the most severe outbreaks.

Severe defoliation by both budworms results in decreased tree growth, tree deformity, top killing, and finally death of trees, often over extensive areas. In fact, feeding habits can vary with the tree host and region. Both

Budworms may begin to feed on staminate flowers and conlets and complete their development on new foliage. In the northern Rocky Mountains, large larvae often feed on cones and seeds of western larch and Douglas-fir, then pupate in the cones.

Host-Insect Interactions

The relationship between the insect and its host tree is mediated by a number of physical and chemical factors. Some of these function in an all-or-none fashion, and their presence, even in small quantities, can render the plant completely unacceptable to some insects while having little effect on others. This so-called qualitative type of defense is exemplified by toxins such as alkaloids, terpenes and cyanide. Other factors function in a more quantitative manner and the degree of host suitability is inversely proportional to the level of the defensive factor in the host. Tannins, terpenes, and foliage toughness are examples of quantitative defenses. The distinction between these two classes of plant defense is arbitrary and not absolute. A given factor can function as a toxin to one insect and a quantitative defense to another. Generally, factors that make certain tree species immune from attack are likely qualitative, whereas factors that influence the susceptibility of a given tree species under different conditions, such as on different soil types, are likely quantitative. A close examination of the various interactions between the budworms and their primary hosts may provide important clues about the processes that make trees susceptible or resistant to damage by defoliation. Various characteristics of the tree or insect can be used to measure or quantify these interrelationships. Many of our speakers will be talking about such tree or insect characteristics as: growth rate, either radial or terminal, or development rate of the insect stages; phenology of tree development--whether it be synchronous or asynchronous with the insect; organic and inorganic compounds within the tree and their influence on the insect; available moisture for the tree and insect; fecundity of the insect; specialized sensors or organs in the insect for detecting special information in the environment or to cope with toxic plant substances. This latter category is relatively new and is just beginning to receive special attention.

The combination of these tree or insect characteristics has evolved into a complex system for the coexistence of

the tree and insect. An examination of the historical record of the spruce-fir forest and recorded outbreaks of the spruce budworms reveals that when this complex biological system is left alone, both tree and insect species continue to exist in spite of vast mortality in populations of each. However, our perceived economic needs will not permit this natural progression.

Budworm outbreaks generally begin when there is an abundant supply of food; population crashes, on the other hand, usually occur only when the food supply is depleted. Various observations and studies have demonstrated that 3 to 4 years of severe defoliation result in a small complement of foliage with a suspected reduction in foliage quality, and therefore correspondingly smaller insects. These insects seem to function normally but their fecundity is clearly reduced (Miller 1963).

Variation in foliar nutrient content has been reported for various host species over time and by location (Shaw and Little 1972, Czapowskyj 1979). This variability is believed to play some role in the population dynamics of the budworm (Miller 1963). At least one research report has been able to provide evidence of a connection between foliage quality and insect development. Shaw, et al. (1978) were able to show that the addition of fertilizer to young balsam fir resulted in larger spruce budworms and higher survival. But attempts to demonstrate a relationship between insect survival or mature insect size and natural variations in foliar components have not been successful (Harvey 1981).

At the inception of a spruce budworm outbreak, a frequent observation is that individual host trees react differently to defoliation. This suggests that there are some differences in susceptibility (McDonald 1981). Unfortunately, as the budworm population increases these differences seem to disappear. This early evidence seems to suggest that a long-term program to develop resistant trees for planting would not be effective. However, these data are not vigorous or substantial. Hence, there still is reasonable expectation of finding and developing less susceptible cultivars of fir and spruce.

All primary host trees seem to be acceptable food sources, although there are some substantial differences between them in their capacity to grow budworms. Intuitive evidence seems to imply that foliage quality has some subtle influence on the population dynamics of the spruce budworms. Foliage quality

differences likely provide some type of fine tuning or feedback information to this complex forest-insect system that might, for instance, induce budworms to disperse.

I believe the participants at this workshop will present research results to show that there are some quantifiable relationships between foliage quality and the budworms' population dynamics. Up to this point, work on foliage quality appears to have been conducted independently by entomologists and physiologists. The participants in this workshop represent these disciplines plus genetics, chemistry, forestry, and modeling. Some people believe that the best way to develop an understanding of the workings of host-insect interactions is through an interdisciplinary team approach. I hope this workshop will at least foster useful dialogue between these disciplines.

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The influence of host type and condition on
bioecology of gypsy moth are discussed from the
point of room and board. Larval establishment
higher on preferred hosts; less than 5%
killed off them. Nonpreferred hosts lost 10-25%
larvae. Susceptibility of gypsy moth larvae to
polyhedrosis virus increased following 1 or 2
years of defoliation. Survival value of insect
feeding locations on the host tree and in the litter
discussed in connection with risk of predation.

"And what does it live on?"

"Weak tea with cream in it."

"Supposing it couldn't find any?" she
suggested

"Then it would die, of course."

"But that must happen very often,"

Alice remarked thoughtfully.

"It always happens," said the Gnat.

Lewis Carroll, Through the Looking Glass

When attempting to describe the bioecology of
gypsy moth, one cannot dissociate this ubiquitous
pest from its host(s). While one tends to relate
insect interactions to herbivory (board),
functions of the host (room) are inextricably
linked with behavior and survival of the gypsy moth.

Fully embryonated eggs overwinter in masses
ranging from 250 to 1,000 eggs. Eclosion occurs
mid-April to early May, depending upon
climatic location and spring weather, usually in
synchrony with host budbreak; asynchrony may occur,
however, in previously defoliated hosts, which tend
to break bud later than normal. Most eggs in a
mass hatch within 3 to 5 days; masses on a site may
persist over a period of 2 to 3 weeks, depending upon
climatic location in the stand and exposure to solar
radiation. First-stage larvae may remain on the
host for several days if conditions are unfavorable
(temperatures <40°F). Otherwise, they move
to the top of trees in response to light, initiate
feeding or suspend themselves on silk, which
permits, permitting the larvae to disperse over
several hundred meters (Mason and McManus 1981).
Dispersal undoubtedly occurs and although the
factors that trigger it are unknown, it is believed
to be related to the vigor of the larvae and means
of host selection (Capinera and Barbosa 1976).
Gypsy moths feed on more than 300 species of trees
and shrubs and these have been grouped loosely into
three categories: preferred, intermediate, and nonpreferred or
rejected species (Bess et al. 1947, Houston 1979).
Species of oak rank among the most preferred.

Once settled, first-stage larvae confine their
feeding to the inner perimeter of the upper leaf
surface. Second-stage larvae feed in inner leaf
perimeter holes, whereas third-stage larvae feed on
leaf margins but expand their feeding activity to leaf
margins. Larvae remain in the canopy; first-stage
larvae rest on the lower leaf surface and second-
and third-stage larvae rest on the undersides of
twigs, branches, or bole; fourth- to sixth-stage
larvae feed on the leaf margins (Leonard 1970).
Normally, males have five instars, females six.
Feeding activity is concentrated in the outer and
upper crown and proceeds downward as foliage is
removed by browsing. Dramatic behavioral change
accompanies molting to the fourth stage; larvae
feed nocturnally and migrate down to resting
locations. Where defoliating populations are dense,
larvae remain in the canopy, have intermittent
feeding bouts day and night, and refrain from
migrating to resting locations. This change in
behavioral and feeding strategy is not understood,
but it may be related to effects of crowding,
necessity to maintain moisture balance, or
abandonment of resting locations whose integrity
has been destroyed by increased radiation due to
defoliation.

Defoliation is usually a 1- to 2-year
phenomenon, with outbreaks being terminated
abruptly by starvation, desiccation, virosis, or a
combination of factors. Forest stands on moist
sites that are repeatedly defoliated tend to become
more resistant to defoliation. This stems from the
fact that preferred tree species, which are
consistently defoliated more heavily, are more
likely to die (Campbell and Sloan 1977).

Is gypsy moth capricious? If so, does larval
behavior reflect this penchant? Host type
influences rates of development, survival, and
fecundity (Hough and Pimentel 1978) but larval
distribution and movement within a forest stand
are poorly understood.

In 1980, I selected a mixed hardwood stand
classified as susceptible to gypsy moth defoliation,
and determined that there were 22 egg masses within
a 1/2-ha study area (considered a sparse population).
All trees >3 inches DBH were burlap-banded and
larvae marked under bands every other day with a
different color acrylic paint for each of eight
tree species. The assumption was made that each
tree had an equal chance of receiving dispersing or
redispersing larvae, and that host selection was
made by instar I and II larvae. Larval abundance
was related to gypsy moth host preference; the
greatest numbers of larvae/ft² of basal area of
host were found on oak, hickory, and aspen; the
fewest on red maple, dogwood, and black birch
(Table 1). Once larvae reached the third stage,
they usually remained on the same host. Less than
5% of the larvae left preferred hosts. Some
redistribution is expected since larvae can be
dislodged from foliage to the ground by wind, rain,
parasites, or predators. They then head for the
nearest vertical object and climb it. Least
preferred hosts lost more instar III larvae than
preferred hosts, which lost none. Additionally,
10 to 25% larval outflux of instars V and VI occurred
on least preferred hosts (Table 2). Redistribution
appeared random but certain preferred hosts (aspen)

Table 1.--Number of gypsy moth larvae captured and egg masses counted/ft.² basal area of host. North Stonington, CT, 1980

<u>Instar</u>	<u>Quaking aspen</u>	<u>Black oak</u>	<u>White oak</u>	<u>Hickory</u>	<u>Black birch</u>	<u>Red maple</u>	<u>Dogwood</u>
III	2.5	5.0	2.3	7.9	3.7	1.9	0.4
IV	32.4	14.3	12.7	26.1	16.7	12.2	2.6
V	118.7	43.1	41.0	60.6	58.6	36.6	14.8
VI	82.2	33.1	38.3	37.0	48.5	17.9	9.9
# Egg masses	48.1	27.7	53.6	21.8	30.4	11.3	1.4

Table 2.--Percent marked gypsy moth larval movement/ft.² basal area by instar and host. North Stonington, CT, 1980

<u>Instar</u>	<u>Quaking aspen</u>	<u>Black oak</u>	<u>White oak</u>	<u>Hickory</u>	<u>Black birch</u>	<u>Red maple</u>	<u>Dogwood</u>
<u>Percent larval outflux</u>							
III	0	0	0	0	3.9	7.7	0
IV	3.6	2.0	4.6	1.7	5.2	4.7	1.9
V	3.3	3.0	3.2	4.3	10.1	14.6	7.8
VI	5.6	3.5	2.3	3.5	2.7	25.8	4.8
<u>Percent larval influx</u>							
III	22.2	0.3	0	0.6	0	0	0
IV	6.0	2.3	2.5	1.2	2.5	3.2	11.5
V	5.6	3.8	4.9	3.0	10.2	6.3	7.4
VI	6.1	2.2	4.5	3.2	8.3	11.8	8.1

gained more marked larvae from other hosts than they lost. In general, there was little evidence of consistent host-switching on preferred or intermediate hosts.

Utilization of the burlap bands increased with each instar reflecting that larval migration down the tree is influenced by the size and abundance of resting locations. Burlap bands are considered highly attractive as resting locations, and egg mass abundance was correlated with the numbers of stage VI females. Only white oak had more egg masses than sixth instars. No evidence of preferential movement from other hosts to white oak was disclosed by our larval marking procedure. Perhaps white oak provided the ideal room and board through preferred foliage and abundant refuges above our burlap bands which precluded the need by all larvae to migrate down the bole where they could be marked.

Pupae are usually found in those resting locations used by larvae that offer the most protection from predators (Campbell et al. 1975). Although this symposium focuses largely on the tree as board for the herbivore, the host may provide room for gypsy moth by providing refuges more secure than others.

The Traveller that is struck by
Lightning, seldom gets home to
Tell his widow.

Ben Franklin's Wit & Wisdom

Analogously, predators can strike quickly and preferentially kill larvae or pupae. The tree provides a number of resting locations (room) each having an associated level of risk to the larva or pupa occupying it. Smith (in press) reported that the type of resting location influenced pupal mortality from predators. Pupae have higher survival when the host provides refuges off the ground that are more secure from predation (Table 3). Forest stands susceptible to gypsy moth defoliation can be classified on several factors including the abundance of these structural features (Houston and Valentine 1977).

The abundance of gypsy moth in Eurasia and East Asia is cyclic and predictable. In North America it is considered episodic, and outbreaks are unpredictable. The consistent level of nonpathogenic mortality reported by Campbell and Podgwaite (1971) in sparse to moderate densities gives credence to the notion that a general decrease in physiological dysfunction

Table 3.--Percent survival of gypsy moth pupae within different resting locations

Density per acre	Location	Eaten by predators		Died (other causes)	Emerged
		Vert.	Invert.		
1000	Flap	13	19	15	52
	Bole	14	17	17	52
	Litter	45	22	8	25
300	Flap	7	15	11	68
	Bole	22	19	11	49
	Litter	42	25	7	26
100	Flap	2	13	6	78
	Bole	3	14	8	76
	Litter	9	37	3	52

From Smith, 1983

larvae could signal the initiation of an outbreak. A number of authors have speculated on foliar condition relative to the abundance of tree defoliators; nitrogen (White 1974), tannins (White 1970, Schultz and Baldwin 1982), and wound-induced proteinase inhibitors (Green and Ryan 1972). Larvae reared on trees that had been artificially defoliated to simulate insect defoliation took longer to develop, suffered more pathogenic mortality, and developed into smaller pupae than those on undefoliated hosts (Wallner and Ryan 1979). Foliar analysis for nutritional elements which occurred in conjunction with this study (Valentine et al. 1983) indicates that higher sugar concentration may influence gypsy moth development and fecundity.

There are subtle secondary effects that are biologically appealing but elusive to document. Increased susceptibility to a pathogen as a consequence of declining host constituency, was noted in the course of our study on the effect of artificial herbivory on gypsy moth. Larvae were reared on host trees receiving 1, 2, or no defoliation and permitted to develop to adults, from which eggs were obtained by within-treatment crosses. Larvae from eggs from each of these 3 populations subjected to different defoliation treatments were challenged with the nucleopolyhedrosis virus (NPV) (Lewis et al. 1981) and LC₅₀ values were determined (Fig. 1).

Only those larvae from eggs produced on trees subjected for 2 consecutive years were significantly more susceptible to NPV than those from undefoliated trees. However, larvae from once-defoliated trees did not appear to be more susceptible to NPV than those from either the primary standard or undefoliated trees. This suggests that host condition can influence the resistance of the insect to a pathogen. Bioassays traditionally have been variable, depending upon the geographic source of gypsy moth, past defoliation history, bioassay methodology, and hence this one test should be viewed as only identifying a potential area for further research.

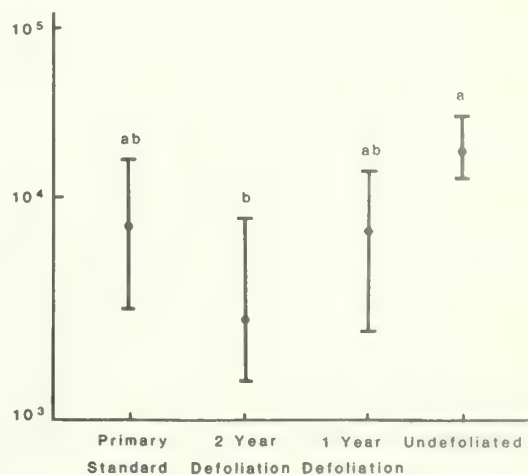


Figure 1--LC₅₀ and 95% confidence limits of gypsy moth mortality challenged with 1976 K standard gypsy moth NPV. Larvae emanated from eggs produced by field reared insects on trees subjected to different defoliation treatments.

The host mediates gypsy moth development, behavior, physiology, and survival within the concept of room and board. It cannot be viewed as a static relationship but a dynamic one, a theme which should be evident throughout this workshop. Are gypsy moth and spruce budworm host relationships iterative processes such that--

The food that to him is as lucious
as locusts, shall be to him shortly
as bitter as coloquintida.

William Shakespeare, *Othello*

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An interdisciplinary approach to resistance breeding is discussed with emphasis placed on documenting genetic variation and developing an understanding of the causal mechanisms responsible for variation in host susceptibility. The specific features and effectiveness of phenotypic and genetic selection are contrasted and examples of documented genetic variation in susceptibility of trees to insects are provided.

Introduction

Despite progress in controlling insects through chemical application and biological manipulation, economic losses from insect damage to forest and ornamental trees remain enormous. Although genetic methods have proved successful in development of insect-resistant crop plants (Maxwell and Jennings 1980), progress in breeding insect resistant trees has lagged behind. As pointed out by Over (1980), that lag can be attributed, at least in part, to relatively long generation intervals in trees and a dearth of knowledge about tree physiology and insect biology. In addition, development of resistance in a long rotation tree such as trees requires an interdisciplinary research effort which has only rarely been put forth. The objective of this paper is to discuss the major components and implications of resistance breeding strategies for trees rather than to provide a review of resistance concepts or physiological mechanisms involved in resistance. The latter information with respect to trees is addressed in reviews by Stark (1965), Gerhold *et al.* (1966), Hanover (1975 and 1980). Hopefully this paper will contribute to the stimulation of interdisciplinary discussions and perhaps cooperative research endeavors among geneticists, physiologists, and entomologists from the northeast.

Components of Resistance Breeding

In the simplest sense, one can identify two major components of the resistance breeding strategy for trees. The existence and accurate demonstration of host variation in resistance (or susceptibility) to insect attack is prerequisite for selection or breeding for insect resistance. Secondly, a thorough understanding of the nature of the underlying mechanism(s) responsible for the observed variation in resistance is important to determine the feasibility and directions of future breeding efforts. A third component, the actual breeding of resistant strains, is dependent upon the success of the first two components. In my opinion, slow progress toward developing

resistant strains of trees (or, at least, strains with reduced susceptibility) can be attributed to the lack of a concerted interdisciplinary effort in the documentation and understanding of insect resistance and its mechanisms. For instance, genetic improvement programs have been established for balsam fir in the Lake States and New England, but none of the many provenance and progeny test plantations have been placed within major spruce budworm regions. As a result, the most productive method for revealing variation in insect susceptibility has not been utilized and no progress has been made in the development of balsam fir resistant to the budworm. With respect to the second component, numerous examples exist of physiologists and biochemists who have thoroughly studied the morphology, anatomy, and/or chemistry of tree populations with purported but not documented resistance to an insect pest. In contrast, enough information on the actual breeding of resistant strains has been generated from crop research (Painter 1966) to provide an adequate foundation of breeding information once the first two components are successfully investigated for a particular host-insect system.

Variation in Host Susceptibility

The development of host resistance to insect attack must be preceded by at least some level of heritable variation in susceptibility to an insect pest. Such genetic variation may occur naturally within species and may be represented by variation among races, provenances, families or individual trees growing side by side in the same stand. In the absence of natural intraspecific variation in susceptibility, interspecific variation may exist and species selection may be a reasonable means of circumventing economic losses resulting from insect attack (Wright and Gabriel 1959; Wilkinson 1981). If species selection is not appropriate, then species hybridization may be an expedient way to generate sufficient heritable variation to allow selection to be productive.

When considering the distribution and biology of the host, the potential for variation in susceptibility of trees to insect attack is expected to be quite high. For instance, tree species have large natural ranges and are, therefore, subjected to a diversity of climatic, edaphic, and biological pressures which tend to promote genetic variation, at least at the population or regional level. Rangewide provenance tests of many species have revealed considerable genetic variation in morphological, anatomical, biochemical, and physiological characteristics, and would suggest that the potential for variation in insect susceptibility might also be high. In addition, despite the increase in tree cultivation during recent years, the vast majority of the forest resource exists in extensive, relatively wild stands. As a result, there probably has not been much gene depletion or a drastic narrowing of the genetic base for most species. Furthermore, tree species are largely outcrossing organisms and are considered to be highly heterozygous with respect to most traits. High heterozygosity can be expected to lead to considerable genetic diversity among

individual trees as well as at population and racial levels. Finally, a substantial level of interspecific compatibility seems to exist within many genera of forest trees and numerous hybrids among species have been produced and documented. Therefore, even in cases where natural variation within a tree species is quite low, the possibility of creating new variation through species hybridization is possible and plausible.

Mechanisms Responsible for Variation in Susceptibility

Upon identifying variation in host susceptibility, it is important to confirm a genetic component to that variation and to understand the underlying causal mechanism(s) responsible for the observed variation. It is important, for instance, to understand whether variation in susceptibility is due to some genetically-controlled avoidance factor (eg. phenological asynchrony) or whether the host is actually capable of resisting the insect. Although resistance can theoretically be identified, and perhaps even captured through breeding, without an understanding of causal mechanisms, the efficiency of breeding and stability of resistance will increase considerably with knowledge of the chemical, physical and/or physiological basis for resistance. This is especially true for long rotation crops such as trees. Instead of "blindly" breeding for resistance, one can select directly for the character(s) which confer that resistance. Or, as emphasized by Hanover (1980), study of causal mechanisms could facilitate indirect selection for traits with a strong genetic correlation with resistance but not causally related to it. Furthermore, physiological investigations of resistance mechanisms may reveal host chemicals which can be used as insecticides or as vehicles of insect behavior modification (Hanover 1980).

Studies addressing mechanisms of tree resistance often examine specific biological properties of the host (and perhaps the insect) and attempt to relate variation in such characteristics to variation in susceptibility to an insect pest. Hanover (1976) has discussed tree resistance to insects in terms of variation in the following broad categories of host characteristics: morphology and anatomy of the host, chemical repellants produced by the host, chemical attractants produced by the host, and the nutritional status of the host. In my opinion, research into mechanisms of insect resistance is necessary for the development of an effective resistance breeding program, but is complicated by environmental influences, tree responses to injury, and developmental, seasonal, and within-tree variation.

Selection for Resistance

Before physiological or chemical mechanisms of resistance can be described and natural variation in insect resistance can be exploited toward the development of resistant strains, it is essential that individual trees or tree populations with inherently low susceptibility to insect

attack be accurately identified. This involves some form of selection. Since "selected" trees will be the source of investigations of resistance mechanisms and may form the basis of a resistance breeding program, it is mandatory that resistance of these trees is documented rather than assumed or inferred. Although often taken for granted the chore of selection for resistance is difficult because of the quantitative and complex nature of the host-insect relationship, environmental influences on this relationship, and interactions between host and insect genotypes and the environment. The major approaches to selection are phenotypic selection of resistant trees in natural or planted stands and genetic selection of families or provenances from replicated progeny tests.

Phenotypic selection

If no previous information on genetic variation in resistance is available for a given host-insect situation, phenotypic selection of unattacked or completely recovered individuals in heavily infested stands is a logical initial step in an artificial regeneration program designed to improve insect resistance. Obviously, in such situations, one hopes that the apparent resistance or recovery ability of the parent tree is inherited and can be transmitted through seed or vegetative propagules to the offspring. For phenotypic selection to be effective, a high selection differential should be maintained (i.e., many trees should be observed but only the one or two best should be selected in each stand) and factors that could lead to escape or an apparent resistant condition must be considered in the assessment of candidate trees (McDonald 1981). However, since the genetic component of phenotypic variation is not readily ascertained without replicated progeny tests, there can be no assurance that progeny will exhibit increased resistance. In fact, there can be no assurance that the selected parent tree has exhibited true resistance. Although phenotypic selection is a reasonable improvement approach when no other information or alternatives are available, it is not the most efficient approach toward initiating a research program involving physiological investigations into resistance mechanisms and actual resistance breeding. Clearly the rigorous demonstration and documentation of genetic resistance to insect attack should be prerequisite to physiological investigations and advanced breeding efforts. Such documentation can not be attained with phenotypic selection in the absence of progeny tests. Unfortunately, the vast majority of research addressing the physiology and genetics of insect resistance in trees has been conducted in the absence of documented genetic resistance of the host.

Specific features of phenotypic selection which limit its utility in screening for an understanding of the nature of insect resistance are as follows:

1. Selection procedures. The effectiveness of phenotypic selection is influenced largely by the selection differential employed and the specific methods utilized in selecting can-

didate trees as well as the heritability of the trait in question. Although it may be possible to standardize selection methods, the selection differential may vary with the size, age, and degree of infestation in the stands.

Escape rather than resistance. Unless a reliable repeatability estimate can be included in the selection criterion, the possibility exists a candidate has escaped rather than resisted attack. Although the probability of escape is inversely proportional to the degree of infestation in the stand, it can theoretically never be zero.

Microsite effects on host and insect phenotype. Localized climatic, soil, or biological factors can influence the morphology, chemistry, and phenology of the host, insect, and/or insect predators and perhaps create a temporarily induced resistance (pseudoresistance). Such confounding environmental factors also muddle interpretation of physiological parameters measured on phenotypically-selected trees.

Developmental and age variation of host. Individual trees may not be attacked because of developmental factors associated with age rather than genetically controlled physiological factors.

Narrow genetic base. Since phenotypic selection is often concentrated in a relatively small portion of a species range, only a small portion of the species genome is assessed. This narrow genetic base limits the potential for developing resistant strains and could lead to some level of inbreeding depression in advanced generation populations.

Nature of genetic control. Even if escape, microsite factors and age can be eliminated as confounding variables and genetic resistance is strongly suspected, the transmissibility of resistance through seed is dependant on the nature of genetic control. If resistance of an individual is the result of a specific combination of non-additive genes, one can not expect a consistently high level of resistance in offspring of that parent.

Stability of resistance. Since for an individual tree there is no way to test the repeatability of resistance over space, it is not known whether the apparent resistance is stable over different environments or is the result of a specific genotype x environment interaction.

Cost and logistics. The cost of maintaining a high selection differential and broad genetic base in a phenotypic selection program can be prohibitive. Furthermore, the logistics of field measurements of physiological traits and of actual breeding are made complicated by tree size, and travel distances as well as confounding environmental factors.

Phenotypic variation in insect susceptibility has been observed for many forest tree species, but only rarely has there been documentation of genetic variation or a physiological explanation for the apparent resistance. For instance, based on phenotypic observations, Hall (1937) reported that "Shipmast" and "Higbee" cultivars of black locust were resistant to the locust borer, but the apparent resistance "broke down" following additional testing. In balsam fir, phenotypic variation in susceptibility to black-headed budworm and spruce budworm has been reported but genetic resistance has never been substantiated (Bakuzis and Hansen 1966). Numerous attempts have been made at phenotypically selecting eastern white pines that are resistant to the white-pine weevil. For instance, Wright and Gabriel (1959) used sophisticated probability estimates and adjustments for microenvironmental factors in assessing weevil resistance but were unable to reliably select resistant trees. In fact, despite phenotypic variation in susceptibility, recent research has indicated that there is no natural resistance of eastern white pine to the white-pine weevil (Wilkinson, personal communication). Finally, in a review paper, Hanover (1980) noted that the American bark beetles and their tree hosts have received more research emphasis than any tree-insect system in the world. Although apparent resistance has been observed in natural populations and considerable research has been done on possible resistance mechanisms, there has been no documentation of genetic resistance to bark beetles among their primary hosts, the pines, spruces, and Douglas-fir (Hanover 1980). Although phenotypic selection has been the foundation of most plant breeding programs, its limitations and expenses with respect to selection of insect resistant trees must be recognized. Wright and Gabriel (1959) provide a realistic account of the effort involved in selecting and testing apparently resistant phenotypes and McDonald (1981) has provided an excellent illustration of the potential complexity of a host-insect system and the numerous factors which could lead to phenotypic variation in response of a host to insect attack.

Genetic Selection

The most productive means for determining the magnitude and nature of intraspecific variation in insect resistance has been carefully designed progeny tests which are replicated within plantations and by several plantations at different locations. Such experiments include rangewide or localized provenance tests, half-sib and full-sib progeny tests and interspecific hybridization studies. These tests may examine progeny of phenotypically selected or unselected parents. In many cases, genetic plantations have been established with tree improvement objectives other than insect resistance in mind. However, if properly designed, such studies can be conveniently and accurately used to assess genetic variation in incidence of attack, degree of injury, feeding and oviposition preferences as well as physiological or biochemical characteristics which may be directly or indirectly related to host susceptibility. Some examples of documented genetic varia-

tion in susceptibility of tree species to insects are included in Table 1.

Some features of progeny tests which contribute to their value in assessing genetic variation in insect susceptibility are as follows:

1. Partitioning of variation. Variation in insect susceptibility and other traits of interest can be quantitatively partitioned into genetic, environmental, and genetic x environment components. As a result, the heritability of specific traits, stability of resistance, and expected gain from selection and breeding can be assessed. Also, genetic variation can be confirmed before expensive and time-consuming studies of resistance mechanisms are initiated.
2. Distribution of genetic variation. The distribution of genetic variation among races, regions, populations, families, and individual trees can be accurately estimated. Such information can help elucidate the nature of variation, such as adaptive strategies, as well as influence subsequent selection and breeding strategies.
3. Broad genetic base. Because trees grown from seed collected throughout a species range can be incorporated into a single study, a relatively broad portion of the species genome can be assessed. As a result, the probability of discovering genetic resistance is increased and the potential for maintaining a broad breeding population is enhanced.
4. Related traits can be accurately measured. Genetic variation in morphological, anatomical, physiological, and biochemical characteristics that may be related to insect susceptibility can be accurately assessed because the measurement of several trees per population or family provides a repeatability estimate.
5. Indirect selection. Genetic correlations among traits can be calculated so the effectiveness of indirect selection for resistance can be tested.
6. Developmental variation. Repeated assessments of variation in insect susceptibility provide an assessment of developmental and age x genetic variation. Juvenile-mature correlations can be estimated and used in judging the reliability of selections.

Table 1. Examples of documented natural genetic variation in susceptibility of tree species to insects.

Host	Insect	Reference
Scotch Pine	Pine Root Collar Weevil	Wright and Wilson, 1972
	European Pine Sawfly	Wright <i>et al.</i> , 1967
	Eastern Pineshoot Borer	Steiner, 1974
	Zimmerman Pine Moth	Wright <i>et al.</i> , 1976
	White-Pine Weevil	Wright <i>et al.</i> , 1976
Eastern White Pine	White-Pine Weevil	Wright and Gabriel, 1959; Garrett, 1972
Austrian Pine	Zimmerman Pine Moth	Wheeler <i>et al.</i> , 1976
Jack Pine	Eastern Pineshoot Borer	Jeffers, 1978
	White-Pine Weevil	Arend <i>et al.</i> , 1961
	Red-Headed Pine Sawfly	Arend <i>et al.</i> , 1961
	Northern Pitch Twig Moth	Hodson <i>et al.</i> , 1982
Douglas-Fir	Sitka Spruce Gall Aphid	Teucher, 1955
	Douglas-fir Woolly Aphid	Meinartowicz and Szmidt, 1978
	Western Spruce Budworm	McDonald, 1979
White Spruce	Eastern Spruce Gall Aphid	Canavera and DiGennaro, 1979
Japanese Larch	Larch Sawfly	Harman and Genys, 1970
European Larch	Larch Sawfly	Genys and Harman, 1976
Norway Spruce	White-Pine Weevil	Holst, 1955
	Black-Marked Tussock Moth	Schonborn, 1966
Balsam Fir	Balsam Twig Aphid	DeHayes, 1981

. Convenience for breeding work. Since all trees are gathered in one place and are all of the same age, breeding can be done with limited travel and usually on trees of relatively small size.

. Immediate production of low susceptible populations. If a genetic component to variation in insect susceptibility is confirmed, open-pollinated seed can be collected from races, populations, or individual trees with low susceptibility and some level of resistance can be expected from the trees produced.

. Phenotypic selection still possible. If genetic variation among populations or progenies is not evident, then phenotypic selection of individual trees can still be practiced in the even-aged test plantations in hopes of exploiting within-family genetic variation.

Although progeny tests are an excellent source of information concerning genetic resistance, they are only effective when located in insect prone areas and when they are of an age (or size) in which the trees are susceptible. For instance, progeny tests may not be an immediate source of information on genetic variation in susceptibility to most bark beetles, since these insects generally attack mature trees. Certainly, forest geneticists and entomologists can and should work cooperatively to insure that forest genetics test plantations are established in areas where insect populations are high so that differential susceptibility can be assessed some time in the future. Perhaps the most serious limitation to genetic selection for insect resistance through progeny tests, is that variation in susceptibility is assessed in unnatural plantations containing a diverse mixture of genotypes. It is possible that insects will select for or against certain seedlots when they are included in a mixed planting, but will attack indiscriminantly in commercial plantings containing trees from one or a few selected seedlots. Despite this potential difficulty, progeny tests still appear to be the only reliable means of documenting a genetic component to variation in susceptibility.

Much of the information documenting genetic variation in susceptibility of tree species to insect pests has been generated from observations of differential damage or feeding in rangewide provenance tests. Other tests, including species and hybrid trials as well as single-parent progeny tests, should also be monitored for such variation whenever possible. Many such tests already exist in the northeast and represent an as yet untapped source of potentially valuable information. Although documentation of genetic variation in susceptibility is an important initial step, studies defining the nature of the variation (eg. resistance vs. avoidance) and elucidating physiological causes for such variation need to be pursued. Cooperative research among geneticists, physiologists and entomologists will likely be the most expedient approach toward the development of forest trees that are resistant to insects.

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DOUGLAS-FIR PROGENY TESTING FOR RESISTANCE TO
WESTERN SPRUCE BUDWORM

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Ample evidence exists that inland
populations of Douglas-fir suffer varying
amounts of defoliation by western spruce
budworm (Johnson and Denton 1975; Williams
1967; McDonald 1981). Such variation in plant
insect association can be the result of the
plant escaping attack in time and place to
actual confrontation between plant and insect
(Harris 1980). Co-evolved genetic interaction
between insect and plant is usually involved in
initiation and preservation of plant
polymorphisms, whether they be morphological or
chemical responses (Gilbert 1982; Berenbaum
1983). Since western spruce budworm
(*Choristoneura occidentalis* Freeman) is a
native insect, there are three reasons for
wanting to know more about the genetic nature
of the Douglas-fir-budworm interaction. First,
genetic interaction may hold the key to
understanding budworm populations release and
crash (Lorimer 1982). Second, a co-evolved and
dynamically balanced genetic interaction may be
keeping damage to levels biologically tolerable
to Douglas-fir, which, if preserved, will
provide the foundation for additional
silvicultural and chemical controls (Browning
1980). The third reason is the possibility of
actively breeding for unnatural levels of
resistance for use in reforestation (Lamb and
Aldwinckle 1980).

All investigations of genetics must begin
with some observable difference in the target
populations. Budworm feeding differences are
readily apparent in western conifer populations
(Williams 1967; McDonald 1981). These
differences could be caused by factors ranging
from asynchronous phenology (Manley and Fowler
1969) to a complex interaction of pheromones,
mating, egg oviposition, and larval feeding
preference (McDonald 1981). The first step to
unlocking these secrets is progeny testing
(McDonald 1982). Such tests have shown the
presence of independent genetic components for
larval feeding (family heritability = 0.43) and
oviposition levels (stand differences) on
17-year-old Douglas-fir (McDonald, in press).
One must conclude that some level of genetic
interaction for one or both of these traits is
functioning. More importantly, these traits
may be reciprocally related to geographic
variation of budworm populations as delineated
by Willhite and Stock (1983) and discussed by

McDonald (in press). Such geographic
association could materially change seed and
breeding zone requirements for inland
Douglas-fir.

Since ecological adaptation has a genetic
basis in Douglas-fir (Rehfeldt 1979), genotypes
were expected to express consistent long-term
growth patterns in response to their adapted
environments. Patterns of radial stem growth
were studied and found to be associated with a
tree's ability to accommodate budworm
outbreaks. The patterns of radial growth of
dead or heavily defoliated Douglas-fir varied
greatly, whereas paired, non-defoliated trees
showed much more consistent growth patterns
from year to year.

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A technique is described to relate
seasonal development of buds of Douglas-
fir, *Pseudotsuga menziesii* (Mirb.) Franco,
larval emergence and survival of wes-
tern spruce budworm (*Choristoneura occi-
dentalis* Freeman) (Tortricidae). Losses
of larvae due to asynchrony of emergence
and bud swelling and the reduced pro-
tection of the bud following flush is
illustrated.

Introduction

Host-insect synchronization is often
important to the survival of the insect;
for example, Witter and Waisanen (1978)
found a six-fold difference in the mean
proportion of buds infested by *Choris-
toneura* spp. between early and late flush-
ing clones of *Populus tremuloides* Michaux.
Information is lacking, however, on losses
of western spruce budworm, *Choristoneura
occidentalis* Freeman that occur because
of poor synchronization of larvae emerging
from diapause and the swelling of the buds
on its host, Douglas-fir, *Pseudotsuga
menziesii* (Mirb.) Franco.

Preliminary studies indicated that
patterns of defoliation of Douglas-fir in
unstable situations could be related
to weather during the bud mining period.
In addition, usually there are trees in
defoliated stands which escape severe
injury (McDonald 1981) and the lack of
synchronization between larval emergence
and bud swelling may be the reason why
these trees are able to retain their
foliage. This paper describes the tech-
niques developed to determine the vari-
ability of host-insect synchrony and how
it affects insect survival and bud dam-
age. An illustration is given of the type
of information which can be obtained with
this technique.

Methods

Five vegetative buds, 1 to 2 m from
the ground, on each of 20 trees per plot
were selected in early spring and tagged
prior to bud swelling and larval emer-
gence. Trees with a variety of heights
were chosen; buds were selected from the
upper crowns of trees 1 m high to the
lower crowns of 30 m trees. Seven plots
were selected to represent a range of
weather patterns and budworm densities;
bud and insect survival and development
were followed on these plots. Buds were
inspected weekly and estimates made of
the following: number of newly mined
needles, presence of larvae, bud develop-
mental stage and type of bud damage.
Mined needles were coded weekly, using
typewriter correction fluid, as mined
needles often dropped off within 2 to 3
weeks of attack. A 10X illuminating mag-
nifier was used to detect larvae in de-
veloping buds without disturbing them.
A hygrothermograph in a Stevenson screen
was set up in a nearby stand opening to
record temperature. Instars of larvae,
collected weekly from adjacent non-study
trees in each plot, were determined and
correlated to degree days calculated
using a 5° threshold.

Nine developmental stages of buds
could be recognized and photoguides were
used to aid in their identification
(Fig. 1):

- 0 - Overwintering stage: uniform dark
brown color, no swelling.
- 1 - White tip stage: bud beginning to
swell, tip becoming sharp and light-
colored.
- 2 - Yellow stage: at least 1/2 of bud
yellow to light brown, individual
scales not conspicuous.
- 3 - White scale stage: bud all light
brown or yellow, scales separated
to reveal white layers underneath.
- 4 - Columnar stage: bud columnar shape
with a rounded tip, green needles
visible beneath semi-transparent
scales.
- 5 - Split stage: bud split open to re-
veal green needles, bud cap may still
be present, needles still tight to-
gether.
- 6 - Brush stage: bud cap gone, needles
flaring but little shoot growth so
needles appear to arise from one
location.
- 7 - Feather duster stage: shoot growth
beginning and needle bases separating,
needles not reflexed.

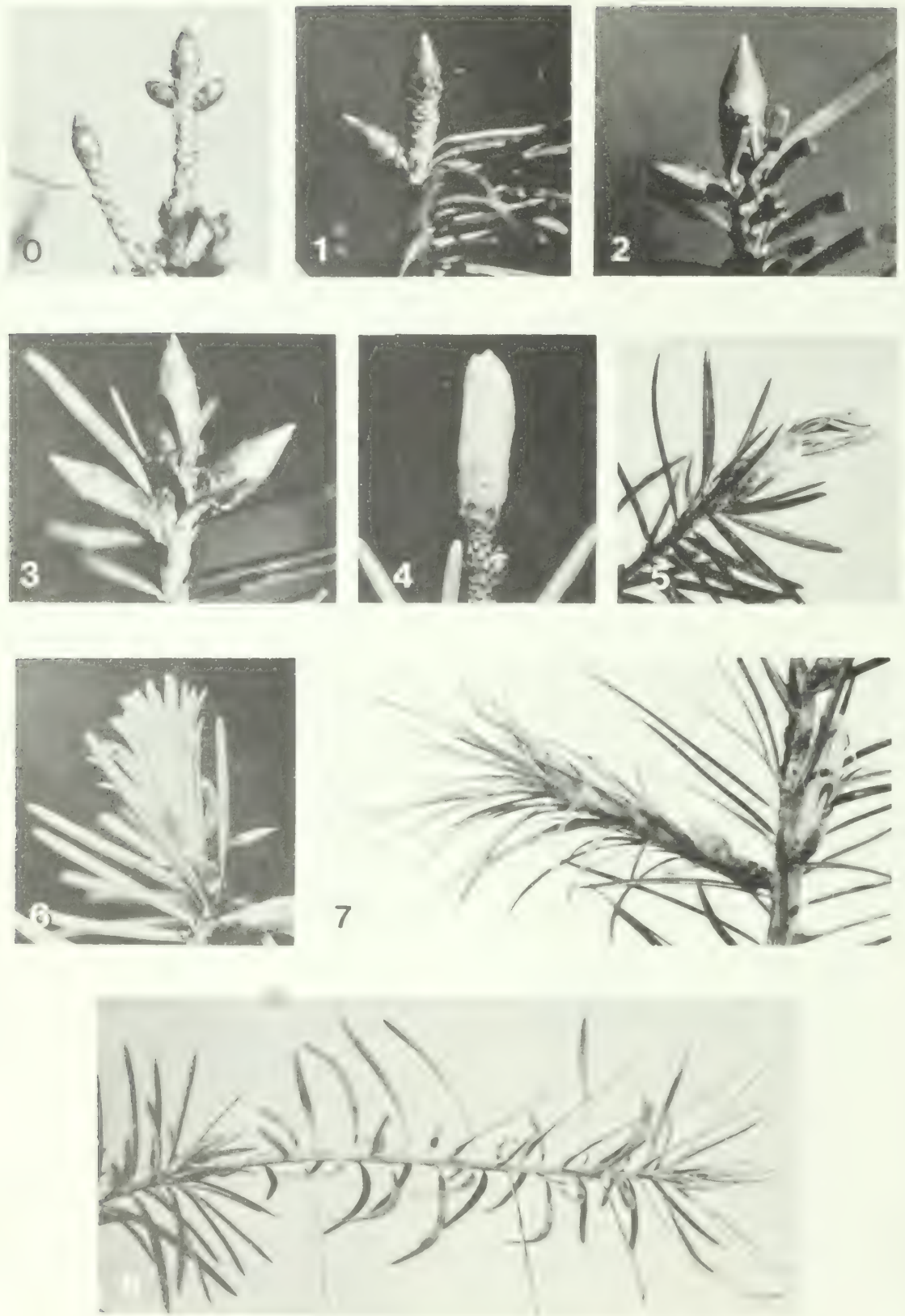


Figure 1. Photoguide of bud development stages 0 to 8.

Shoot growth stage: needles reflexed and needle bases separated, new stem obvious.

These are similar to the six phenological stages recognized by Nienstaedt King (1970) for *Picea glauca* (Moench) and used by Pollard and Ying (1979) studies of variability of flush rates.

Bud damage classes were noted as follows:

bud or shoot not attacked.

bud attacked and killed before it flushed.

bud attacked, still alive, but has not flushed, extent of damage cannot be estimated.

3 - bud flushed and attacked, <75% of the needles have been damaged.

4 - bud flushed and attacked, >75% of the needles have been damaged, next year's bud healthy.

5 - bud flushed and attacked, >75% of the needles have been damaged, next year's bud killed.

Results

A time series graph can be constructed for each plot, one of which is illustrated in Figure 2. In this plot, larvae first began needle mining on May 6 and continued until May 31. By this date, half of the buds had swollen to stage 2 (Fig. 1), and the scales had thinned



Figure 2. A comparative time series graph for the Hart Ridge, B.C., plot in 1980. Events recorded are bud developmental stage (0-8, X10) insect developmental stage (instar 2 to 6, X10 and pupae), larval density (per 100 buds), number of buds with mined needles (per 100 buds), percent of buds with >75% of the needles eaten.

enough so that larvae could penetrate the buds; average insect development stage was instar 2.9. Assuming one larva per newly mined bud, there was a decrease in larval numbers at this stage, presumably because all larvae could not find suitable buds. However, after bud stage 2 was reached, larval density slowly increased until June 20. This may have been caused by continued larval emergence from overwintering diapause and/or larval redistribution over the trees, thereby increasing the ranks in the buds under study. However, when buds reached stage 6 (372 degree days), the larvae lost their protective niches and their numbers began to decrease rapidly. Average insect development at this point was instar 4.8. By pupation (610 degree days), only 13 of the 48 present at stage 6 had survived.

Bud damage began as soon as larval penetration could be made at stage 2 and progressed steadily through until pupation (Fig. 2). Buds suffering 75% or more defoliation were noted first at 360 degree days and the percent of buds with this severity of attack reached 24% by the time of pupation. The final average defoliation in this plot was 57%, with 85% of the buds showing some damage.

This technique is most useful on a comparative basis and can be used to relate budworm survival to bud phenology sites, yearly weather or phenological races of trees.

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Caged field studies indicate that the
foliage of western larch is apparently less
suitable to western spruce budworm larval
development than the foliage of Douglas-
fir, subalpine fir, and Engelmann spruce.

Western larch, Larix occidentalis
Nutt., is sometimes listed as a major host
of the western spruce budworm,
Choristoneura occidentalis Freeman,
(Furniss and Carolin 1977). Clearly,
budworm larvae feed on larch and produce
damage (Fellin and Schmidt 1967; Schmidt
and Fellin 1973). However, numbers of eggs
on larch are usually low suggesting that
populations on this species stem partly
from incidental oviposition but mostly from
massive dispersal in the 1st and 2nd
instars (Wissenbach 1982). Also, our
observations have indicated, that although
larch may support large numbers of early
instars, few seem to survive to the pupal
stage.

Large larvae from a laboratory colony
were caged in the field on several of the
listed host species to check the relative
suitability of western larch as a host.
Data were collected on survival and pupal
weight when feeding was completed; this
note reflects the results of that study.

Methods

Two field sites in north-central
Washington were chosen to obtain four host
species representing different genera. One
site (B. S. Place) contained Douglas-
fir, Pseudotsuga menziesii var. glauca
(Beissn.) Franco, and larch; the other site
(Twisp River) contained Douglas-fir,

subalpine fir, Abies lasiocarpa (Hook.)
Nutt., and Engelmann spruce, Picea
engelmannii Parry ex Engelm. Douglas-fir
was tested on both sites to be sure there
were no major differences between sites.

At each site, five open-grown trees
per species of approximately the same
height (4-5 m) were selected for testing.
Fine-mesh nylon bags were placed around 45-
cm tips of four branches per tree about 2 m
from the ground. To monitor temperature,
one tree per species had thermocouples on
the under-surface of branches within the
nylon bags and on uncovered branches.

The nylon bags were stocked with
laboratory-reared western spruce budworm.^{3/}
The overwintering larvae had been exposed
to cold temperatures to break diapause and
timed to reach the 5th instar at about the
same time as the field population. The
test larvae were fed a standard budworm
diet until they molted to the 5th instar,
at which time they were randomly assigned
to a specific nylon bag. Only five larvae
were placed in each bag to ensure adequate
current foliage to complete development.
All cages at one field site were fully
stocked within 2 days. Enough 5th instars
were available at the proper time to infest
five trees of Douglas-fir and Engelmann
spruce at Twisp River; subalpine fir at
Twisp River and the tree species at B. S.
Place had four trees stocked with larvae.

Budworms in bagged branches were
examined and temperatures from
thermocouples recorded at 2- to 3- day
intervals. Pupae were removed, sexed, and
weighed to the nearest milligram within 72
hours of pupation. Pupal weight and
survival were used to determine the
adequacy of each host as a food source.
Weights of naturally occurring pupae from
Douglas-fir at B. S. Place were compared
with those of pupae bagged on Douglas-fir
at that site. Weights of only those pupae
that successfully produced adults were used
in the analyses. The data were analyzed by
ANOVA; differences were tested by a
Duncan's multiple range test (1955)
incorporating Kramer's (1956) modification
for unequal sample size.

^{3/} Supplied by Dr. M. Martignoni,
Forestry Science Laboratory, Corvallis,
Oregon.

^{1/} Lepidoptera: Tortricidae.

^{2/} The research reported here was
financed in part by the Canadian/United
States Spruce Budworms Program - West.

Results

All individuals that survived to the pupal stage and emerged were pooled for each host in the analysis because survival and pupal weights were not significantly different between branches or trees.

Survival ranged from 49% on larch to 88% on Douglas-fir at Twisp River (Table 1). Survival on larch was clearly much lower than on the other species. The same pattern occurred when comparing pupal

weights from the four hosts. Male and female pupae were significantly lighter on larch than on the other species (Table 2). The heaviest males were obtained from Douglas-fir at B. S. Place; the heaviest females were also obtained from Douglas-fir at B. S. Place, but they were not significantly heavier than those on Douglas fir at Twisp River. In general, the bagged pupae on Douglas-fir were heavier than those collected from the natural population.

Table 1. Percent survival to adults of western spruce budworm reared on various hosts in north-central Washington, 1981.

Location	Host	Number Started	Number Adults	Percent Survival
Twisp River	Douglas-fir	100	88	88
	Subalpine Fir	80	67	83
	Spruce	100	82	82
B. S. Place	Douglas-fir	80	67	83
	Larch	80	39	49

Table 2. Pupal weights of western spruce budworm reared on different hosts in north-central Washington in 1981.

Location	Host	n	Males \bar{x} (mg) ^{a/}	S.E.	n	Females \bar{x} (mg) ^{a/}	S.E.
Twisp River	Douglas-fir	50	90.2 b	1.70	38	121.6 ab	4.75
	Subalpine Fir	35	76.4 c	2.13	32	91.3 d	2.92
	Spruce	45	80.8 c	3.10	37	108.3 bc	4.29
B. S. Place	Douglas-fir	46	103.9 a	2.70	21	135.5 a	5.45
	Larch	17	41.5 d	2.67	22	43.2 e	3.49
	Natural	26	81.6 bc	2.43	33	104.5 cd	2.73

^{a/} Any two means by sex not having a common letter are significantly different at the .01 probability level.

Discussion

Reduced pupal weights and poor survival (49%) of western spruce budworm reared on larch may indicate that the foliage does not provide late instars with proper nutrition for normal development, or

the foliage may contain materials that produce an antibiosis in the insect. Ryan (1979) found that survival and growth of the larch casebearer, Coleophora laricella (Hbn.), were associated with the stage of foliage growth. Under the conditions of the 1981 experiment, the

laboratory stock may not have adapted as well to the larch foliage as to that of the other species. The report by Fellin and Schmidt (1967) of severe defoliation of larch does not mention when the damage occurred. The defoliation may have been caused by early larval feeding from high populations after spring dispersal (Beckwith and Burnell 1982). The rough bark of larch provides an excellent substrate for overwintering larvae that land on the trees during fall dispersal; large populations would thus be in place on the tree when the larvae emerge in the spring. Larch foliage breaks in the spring much earlier than Douglas-fir or true fir, thus new growth is available for early emerging larvae. The disappearance of larger larvae from larch could result from excessive predation, off-tree dispersal because of inadequate foliar nutrition, or both (Beckwith and Burnell 1982). Spur-shoot foliage apparently offers inadequate protection for large larvae. Preliminary work in 1980 also suggested that the foliage did not provide proper nutrition to produce pupae of normal size; however, larvae may still feed on the foliage as Chew (1980) found that larvae do not necessarily reject plants that fail to support larval growth in favor of those that do.

Why the natural pupae collected from Douglas-fir were significantly lighter than the caged insects on Douglas-fir is not clear. Feeding in the natural population may have been interrupted by predators, parasitoids or excessive wind movement. The experimental larvae may have been protected from these factors by the nylon mesh cages. The slightly different temperatures in the cages probably would not account for increased pupal weight; air temperatures in the cages were only 1 to 2°C higher when the cages were in the sun and equal to or slightly lower in shade. The artificial diet fed the first three instars of the test may have given them a growth advantage over the natural population. Also, the laboratory population may have larger pupae because of genetic differences.

A phytophagous insect must be able to complete its life cycle solely upon a plant species and be normal in all respects for that plant species to be considered a major host. An antibiosis response (delayed development, small size, or reduced

fecundity) would indicate that the plant is marginal as a host (Painter 1968). Foliage of western larch is apparently less suitable to budworm development than foliage of Douglas-fir, true firs, and Engelmann spruce.

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ABSTRACT

The utilization of stored lipids (fat) for energy metabolism appears to be a fundamental process for many biological systems especially during the early stages of their development. Participation of the glyoxylate cycle (GOC) together with other metabolic sequences like gluconeogenesis and beta oxidation are necessary for the conversion of lipids to carbohydrates. This report describes the distribution of the GOC in amongst biological systems and examines its importance to the development and existence of biological cells under different physiological conditions. The report also describes some of the work which focuses on the role of the GOC in parasitic (*Caenorhabditis elegans*) and parasitic (*Ascaris lumbricoides*) nematodes. It is possible to demonstrate the *in vivo* and *in vitro* inhibition of isocitrate lyase (ICL), a key enzyme of the GOC operating in these nematodes by malonate. Finally this report explores the possibility of using target specific inhibitors like itaconate to control spruce budworm (*Pristiphora fumiferana*), populations.

Introduction

The spruce budworm is widely distributed in North America including Canada. The organism has been declared as an insect pest of national concern. It causes extensive defoliation and mortality to a wide variety of coniferous tree species including balsam fir (*Abies balsamea*), white spruce (*Picea glauca*), red spruce (*Picea canadensis*), and black spruce (*Picea mariana*). Outbreaks of spruce budworm in Canada have been reported as early as 1700's (Blais, 1965). Timber losses in recent outbreaks when converted into dollar values amount to millions of dollars. Although the life cycle and the population dynamics of the spruce budworms have been examined, no information is available on the biochemistry and physiology of the embryonating eggs of the developing larvae. The energy metabolism at the different developmental stages of the spruce budworm has not been examined. The examination of the energy metabolism of the embryonating eggs and the developing larvae of spruce budworm may result in information which may be used to come up with target specific inhibitors directed against the key enzymes of the GOC.

Glyoxylate Cycle And Its Distribution In The Nature

Kornberg and Krebs (1957) first revealed the evidence for the function of the GOC in replenishment of the tricarboxylic acid (TCA) cycle intermediates depleted during the gluconeogenesis and the amino acid biosynthesis. Its operation has been shown to be essential in cells which depend on acetate, ethanol, lipids, hydrocarbons and C_1 compounds for its carbon and energy needs (Cioni et al, 1981). Although the GOC was first described in bacteria utilizing acetate or ethanol as sole carbon and energy sources this pathway has a large representation in nature being operative under various nutritional and physiological phases of the life of many organisms.

The glyoxylate pathway can be described as a cyclic set of reactions starting from isocitrate and returning to it. This cycle (Fig. 1) allows the transformation of two acetate (as acetyl-CoA) into one of succinate. Five enzymes that participate in this catalysis include isocitrate lyase (ICL), malate synthase (MS), malate dehydrogenase (MDH), citrate synthase (CS) and aconitase (ASE). Reactions 1 and 2 (Fig. 1) immediately reveal the anaplerotic significance of the two enzymes (ICL and MS) as they produce two TCA cycle intermediates (succinate and malate) starting from one TCA cycle six-carbon compound (isocitrate) and a molecule of the substrate of the cycle (acetyl-CoA). The glyoxylate cycle thus replenishes intermediates of the TCA cycle and conserves carbon that would otherwise be completely oxidized and lost to biosynthetic pathways. This replenishing function of the GOC has been termed 'anaplerotic'.

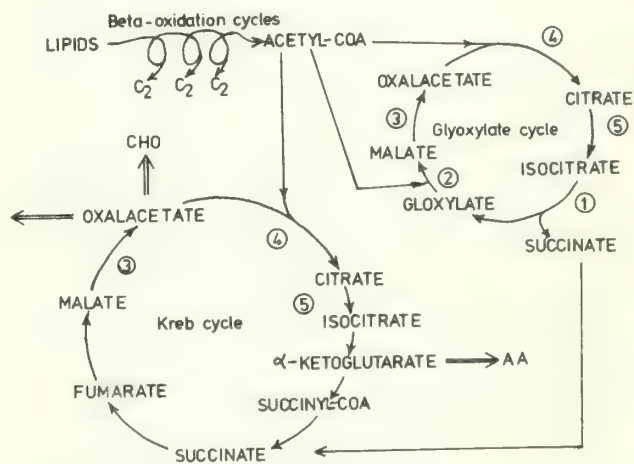


Fig. 1. Relationships between Krebs cycle, beta-oxidation and glyoxylate cycle. (AA = amino acid for biosynthesis; CHO = carbohydrates; C₂ = two carbon units, acetyl CoA).

The ICL has been found in bacteria (Woolfson

and Krulwich, 1972; Ozaki and Shio, 1968; McFadden and Howe, 1962, 1963; Sariaslani *et al.*, 1961; Chell *et al.*, 1978;), algae (John and Syrett, 1967; Haigh and Beevers, 1964a; 1964b; Dunham and Thurston, 1978; Collins and Merrett, 1975), pteridophytes (Gemmrich, 1979), gymnosperms (Firenzuoli *et al.*, 1968; Vani *et al.*, 1973), angiosperms (Gientka-Rychter and Cherry, 1968; Kagawa *et al.*, 1973; Ihle and Dure, 1972; Theimer and Rosnitschek, 1978; Khan *et al.*, 1977; Vani *et al.*, 1979; Lango *et al.*, 1975; Calvin and Beevers, 1961; Ford *et al.*, 1976; Tester, 1976), fungi (Maxwell *et al.*, 1975; O'Sullivan and Casselton, 1973; Flavell and Woodward, 1970; Reisener and Jager, 1967; Polakis and Bartley, 1965; Mendgen, 1973), protozoa (Hogg and Kornberg, 1963; Muller, Hogg and DeDure, 1968; Lovel *et al.*, 1974), and nematodes and trematodes (Barrett *et al.*, 1970, 1971; Colonna and McFadden, 1975; Rothstein and Mayoh, 1964, 1965; Prichard and Schofield, 1979; Patel and McFadden, 1977). The presence of the ICL has also been reported in the prepupae and pupae of the *Prodenia eridania* (Carpenter and Jaworski, 1962). It must be pointed out that the GOC has never been detected in animals more highly evolved than worms such as nematodes and trematodes.

The Physiological Role Of The GOC

In higher plants the GOC occurs in germinating seedlings of numerous plants where it is required for the conversion of stored lipids into carbohydrates which then form the source of energy during germination. In germinating spores of fern a similar lipid to carbohydrate transformation occurs. If one examines the levels of ICL and MS in the germinating fatty seeds a typical pattern is observed (Fig. 2). The increases in ICL and MS follow a simultaneous decrease in the total lipids in these seeds. The enzymes of the GOC are compartmentalized in single membrane, subcellular particles called 'glyoxysomes'. It must be noted here that glyoxysomes, unlike mitochondria, have a single bounding membrane.

In algae, the GOC participates in the utilization of acetate for growth when photosynthesis is not operative and carbohydrates are not available. The enzymes of the GOC have also been reported in the trematode, *Fasciola hepatica* (Prichard and Schofield, 1979), which is a mammalian liver fluke. In the case of *Fasciola hepatica* adults which live in the bile duct, it has been suggested that the GOC enzymes are involved in the production of glycogen to be incorporated into eggs which are very rich in glycogen (Horstmann, 1962; Wilson, 1967).

Although the data suggests that ICL and MS are scattered through out metazoan phyla, almost nothing is known about the function of this cycle in developing larvae and/or adult worms. Indeed only in the case of *A. lumbricoides* and *C. elegans* has the function of the GOC been clearly established (Rothstein and Mayoh 1965; Patel and McFadden, 1977, 1978, 1978b, 1978c). It has been shown that extensive synthesis of the dis-

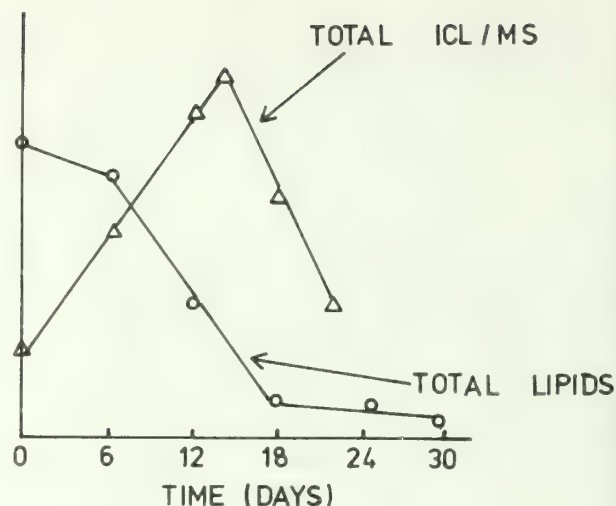


Fig. 2. Levels of MS and ICL (Δ) and total lipid (○) content during germination of seeds.

accharide, trehalose, occurs in the developing embryos of *A. lumbricoides* at the expense of fat and that this conversion correlates with the appearance and disappearance of ICL and MS (Barrett *et al.*, 1970). Quite recently Rubin and Trelease (1976) have found that the disaccharide resynthesis after embryonation accompanies the disappearance of triglyceride droplets found largely in the posterior half of the larvae. Dense microbody-like granules, restricted to the lipid-body region, are considered as possible subcellular sites for the enzymatic conversion of lipids to carbohydrates (Rubin and Trelease, 1977a, 1977b).

Materials And Methods

Materials. Succinic acid, itaconic acid, dithiothreitol (DTT), glutathione (GSH), DL-isocitrate, morpholinopropanesulfonic acid (MOPS), beta-mercaptoethanol, Tris-HCl, and ethylene diamine-tetraacetic acid (EDTA) were purchased from Sigma Chemical Co. Sephadex G-200 came from Pharmacia Fine Chemicals. All inorganic chemicals were commercially available and were of analytical grade.

Organisms And Growth Conditions.

Caenorhabditis elegans were kindly supplied by Dr. R.L. Russel, University of Pittsburgh, Pittsburgh, U.S.A. *Escherichia coli* K8-5m (CGSC strain No. 4868) is a mutant which fails to grow on acetate as a sole source of carbon and lacks isocitrate lyase when grown on glucose. The method for cultivation of *C. elegans* under monoxenic growth conditions has been reported earlier (Colonna and McFadden 1975; Patel and McFadden 1976).

Freshly recovered female Ascaris lumbricoides containing eggs were purchased from Nebraska Scientific Co., Omaha, Nebraska, U.S.A., shortly after preservation in 2% formalin. Eggs, obtained after removing the reproductive tracts from female worms, were embryonated for 22 days and treated with hypochlorite by the method described by Hanna and McFadden (1975) prior to breakage.

Preparation Of Crude Enzyme Extracts.

Crude extracts of C. elegans and A. lumbricoides were prepared by the methods of Patel and McFadden (1977).

Enzyme Assays

Isocitrate lyase was assayed at pH of 7.7 according to Roche *et al* (1971) with the inclusion of 0.2M phenylmethylsulfonyl fluoride (PMSF) in assay buffer. Other enzymes of the GOC namely, citrate synthase, citrate synthase, fumarase and isocitrate lyase were also examined but will not be discussed here.

Protein concentrations in crude extracts were determined by the method of Lowry *et al* (1951).

Results

When washed eggs of A. lumbricoides were incubated in a solution of 0.1 N sulfuric acid and agitated on a shaker at 30°C ICL activity began to appear in the embryonating eggs on the fifth day. It reached a peak on day 18-20 and then to decline gradually thereafter. In the case of C. elegans the situation is slightly different. This non-parasitic nematode is self-fertilizing (hermaphroditic) worm living in soil where it feeds on bacteria. A fully grown worm measures about 1 to 1.5 mm in length. In a laboratory it can be cultivated just like bacteria growing either axenic or monoxenic growth conditions. A single worm takes about 48 hrs from an egg stage to mature into a fully grown adult worm. During this short period it undergoes four molts representing the four larval stages, namely L₁ through L₄ (Fig. 3). Methods to obtain synchronous cultures of C. elegans have been described in our earlier report (Patel and McFadden, 1978).

The levels of ICL in the embryonating eggs and larvae derived from them were monitored. The results in Figure 4 shows the specific activity of ICL was minimum in the zero-time sample representing unhatched embryonating eggs. The enzyme activity in the 48 and 60 hr samples was undetectable. These samples contained young adult worms of uniform length bearing no eggs. These data suggest that ICL may have an important role in the chemistry of the embryonating eggs and the developing larvae, and that the adult worms may not require the enzyme for its survival.

Itaconic acid (methylene succinic acid) was used as a target specific inhibitor to test in

TIME
(HOURS)

0	HATCH, 600 SOMATIC CELLS, FURTHER GROWTH BY ENLARGEMENT OF THESE CELLS.	
6-11	FIRST LARVAL MOLT	L1 STATE
18	SECOND LARVAL MOLT	L2 STATE
26	THIRD LARVAL MOLT	L3 STATE
36	FOURTH LARVAL MOLT	L4 STATE
		ADULT
45-46	EGG LAYING BEGINS	
	4 EGGS PER HOUR INITIALLY	
	9 EGGS PER HOUR AFTER 92 HOUR.	
	EGG LAYING ENDS AFTER 120 HOUR.	

Fig. 3. Developmental stages in the life of Caenorhabditis elegans. (from Hirsch *et al*. 1976).

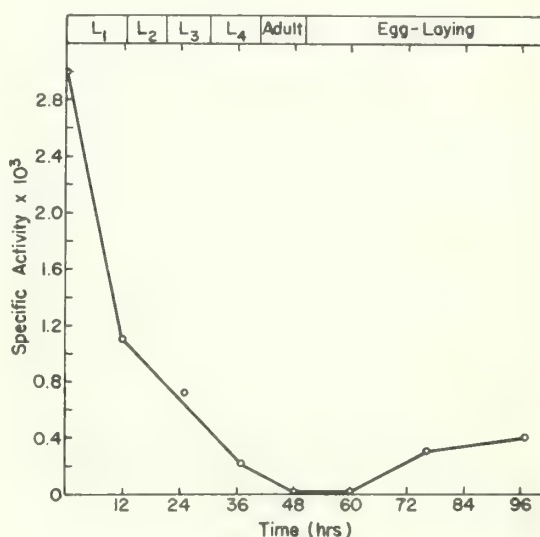


Fig. 4. Levels in ICL during synchronous growth of C. elegans larvae.

vivo and *in vitro* inhibition of ICL of A. lumbricoides. Figure 5 shows that itaconate inhibits the growth of C. elegans. At a 60 mM concentration the inhibitor caused 50% reduction in the growth of C. elegans in a random monoxenic culture of C. elegans. However, its effect on the growth of C. elegans in a random axenic culture was much pronounced. The results in Table 1 shows that 5, 30 and 60 mM itaconate caused 70, 93 and 99% inhibitions, respectively.

Table 2. Effect of itaconate on the growth of *C. elegans*.^a

Days	Worms/ml $\times 10^{-3}$				
	Itaconate				
	0.0 mM	5 mM	15 mM	30 mM	60 mM
0	0.40	0.4	0.40	0.40	0.40
2	0.60	0.46	0.26	0.20	0.20
5	2.80	2.06	1.60	0.60	0.20
6	8.60	2.52	1.87	0.60	0.20
8	12.00	7.00	3.40	2.40	0.20
10	41.00	12.66	—	2.80	0.27

^aEach of the 500-ml Erlenmeyer flasks contained 60 ml of axenic medium with the indicated concentrations of itaconate. The flasks were inoculated with 0.5 ml of a random population of *C. elegans*, and incubated on a shaker in a Psychroterm drawn from each flask at the given times to determine the worm population as described in MATERIALS AND METHODS.

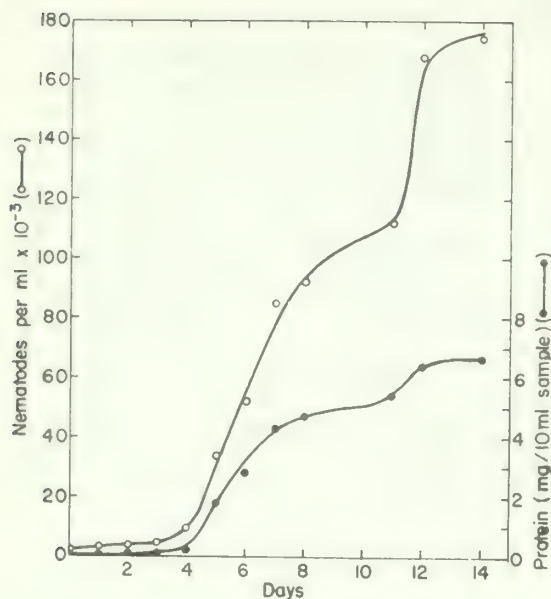


Fig. 5. Growth inhibition of *C. elegans* by itaconate (60 mM) in monoxenic cultures.

shown that ICL level is higher during embryogenesis and L₁ larvae stage after eggs were allowed to hatch in a monoxenic medium (Fig. 4).

Table 1. Growth of *C. elegans* in the presence and absence of metabolic inhibitors^a.

Day	Worms/ml $\times 10^{-3}$						
	Control	Itaconate			Oxalate	Maleate	Succinate
		10 mM	30 mM	60 mM	10 mM	10 mM	10 mM
1	3.8	3.8	3.8	3.8	3.8	3.8	3.8
3	9.1	7.2	6.0	3.2	8.0	8.8	8.9
5	64.7	32.1	13.8	6.3	51.5	32.0	67.9
7	162.0	106.2	22.5	9.2	146.9	139.0	175.0

^aEach 250-ml flask contained 15 ml of axenic medium plus one of the above filter-sterilized compounds. Worm counts were made by direct microscopic examination as described. All the flasks were shaken at 120 rpm and 23°C in a Psychroterm incubator.

In order to test the specificity of itaconate inhibition of growth of *C. elegans* other compounds shown in Table 2 were tested. Itaconate in 10, 30 and 60 mM concentrations resulted in 34, 86 and 94% inhibitions, respectively. In contrast, oxalate and maleate caused negligible inhibition of the growth of *C. elegans* while succinate showed a stimulatory effect. The effect of itaconate upon the growth of synchronously growing monoxenic culture of *C. elegans* was maximum. In this case the inhibition is almost 100% (Fig. 6). This is not unexpected since itaconate may inhibit ICL in embryos and L₁ larvae of *C. elegans*. This result compliments nicely the earlier observation in which it was

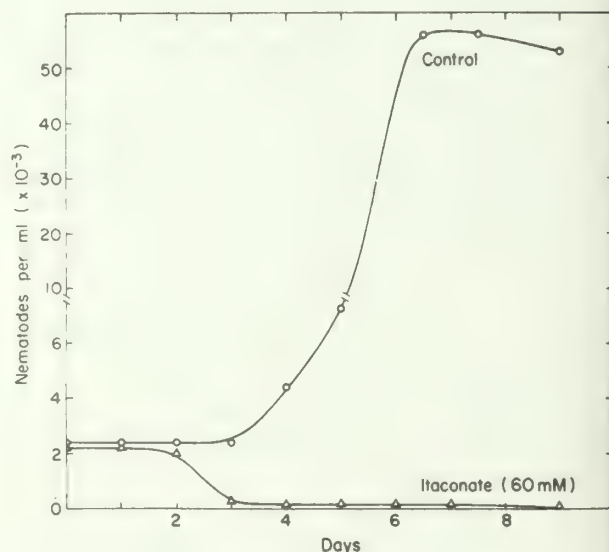


Fig. 6. Effect of itaconate (60 mM) on the synchronous growth of *C. elegans* in a monoxenic culture.

Increasing concentrations of itaconate caused higher *in vitro* inhibition of ICL in crude extracts of *C. elegans* (Fig. 7). More than 80% inhibition was observed with 10 nanomolar concentrations of itaconate. A similar pattern of inhibition was also observed with ICL in crude extracts of *A. lumbricoides*. Kinetic studies using the enzyme from both the organisms (*C. elegans* and *A. lumbricoides*) indicate itaconate is a non-competitive inhibitor of ICL. The apparent inhibition constants were 19 micromolar for *C.*

C. elegans enzyme and 7.3 micromolar for A. lumbricoides enzyme.

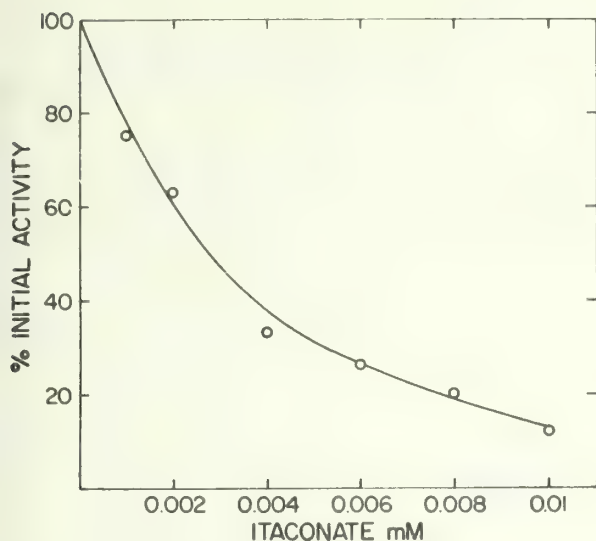


Fig. 7. In vitro inhibition of ICL of C. elegans by itaconate.

Discussion

The above results indicate that GOC cycle plays an important role in the biochemistry of embryonating eggs and the young developing larvae of C. elegans and A. lumbricoides. In the case of C. elegans it was possible to demonstrate that itaconate acts as a specific inhibitor of ICL in vivo as well as in vitro. The inhibitor caused drastic reduction in the population of the nematodes in monoxenic and axenic cultures.

An important question is raised here. Is it possible to employ target specific inhibitor like itaconate or other such compounds to blockade the GOC and hence prevent the growth of an organism? The answer is yes. The experiments described above suggest that itaconate may be used as a target specific inhibitor to prevent the growth of nematodes like C. elegans.

The work in McFadden's laboratory showed that ICL in crude extracts of Ps. indigofera and N. rassa were inhibited by itaconate, an analogue of succinic acid. The enzymes of the bacterial and the fungal sources have been purified to homogeneity. The inhibition studies using the purified enzymes indicated that itaconate is a competitive inhibitor with respect to succinate in the condensation (or reverse) reaction and is noncompetitive with respect to glyoxylate. In the forward (cleavage) reaction the itaconate acted as a non-competitive inhibitor. In the present study itaconate was found to be non-competitive inhibitor when ICL from C. elegans and A. lumbricoides were tested.

Recently Bruce McFaddens group at Washington State University, Pullman, have shown that itaconate can bring about in vivo inhibition of Pseudomonas indigofera growing on acetate. The results obtained with cultures of C. elegans compliment their finding. The inhibition of isocitrate lyase by itaconate in the case of Tetrahymena pyriformis in vitro and in vivo has been reported by Dang and Cook (1981).

If one examines the life cycle of the spruce budworm one finds some interesting features which raise important practical questions. In Newfoundland in late July or early August the moth lays eggs which embryonate and hatch into first instar larvae in about ten days. These larvae do not feed but are very active, moving on branches or hanging by their silky threads. They soon begin to look for a place in preparation for wintering over. They prepare hybernacula in which the second instar larvae winter over. These larvae hibernate until the arrival of the spring in May or early June. The second instar larvae become active and undergo molting to complete the remaining developmental stages to produce sixth instar larvae. The pupation occurs in July and August. The young moth appears and begins to lay eggs shortly thereafter.

There is some similarity in the early developmental stages in the life of C. elegans and the spruce budworm. Perhaps they resemble in their biochemistry and physiology during their early stages. If this is true then it may be possible to use itaconate as a target specific inhibitor to prevent the progress in the development of the larval stages of the spruce budworm. Before such practical approach is adopted it is necessary initially to do some fundamental research to investigate the biochemistry and physiology of the embryonating eggs and developing larvae of spruce budworm.

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SPRUCE BUDWORM^{1/} REARED ON THREE HOST FOLIAGES AND ARTIFICIAL MEDIUM.

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Western spruce budworm were reared on three host foliages and artificial medium. Trace element analyses showed large differences in elemental concentrations between food sources and only minor differences between insect life stages. Discriminant analyses were carried out to test the distinctiveness of adult chemoprints from each rearing regime. Fe, Cu, and Zn were distributed differentially between egg mass and other parts of the female moths. Females reared on artificial medium weighed more than foliage-fed females.

Introduction

The usefulness of a trace element "chemoprint" of an insect, as determined by simultaneous multi-elemental analytical techniques such as X-ray energy-dispersive spectrometry (XES) (Bertin 1978), has relied on a basic assumption that the elemental profile of an insect reflects its host plant and thus indirectly the soil and bedrock geology. The western spruce budworm, Choristoneura occidentalis Freeman, has been shown to have a sufficiently distinctive area specific chemoprint to distinguish adults from two stands 2.6 km apart (McLean et al. 1979). In addition, considerable among tree variation was also reported. The objective of this study was to determine if there was significant variation between the chemoprints of western budworm reared on three host foliages, Douglas-fir (DF), Pseudotsuga menziesii (Mirb.) Franco, Engelmann spruce (ES), Picea engelmannii Parry, Grand Fir (GF), Abies grandis (Dougl.) Lindl.,

and artificial medium Bio-Mix #9769 .

Quantitative data were developed in this study to overcome legitimate criticisms raised on the reliability of elemental assignments in earlier studies of salmon, snowgeese and ambrosia beetles using X-ray energy spectrometry (Bowden et al. 1979).

Methods

Fourth instar western spruce budworm (WSBW) larvae were collected on hand clipped from infested trees at Oregon Jack Creek, British Columbia, in June 1978. These larvae were laboratory-reared on new DF, ES and GF foliages as well as artificial medium. The DF and GF foliage were collected fresh from the U.B.C. Endowment Lands as required. The ES foliage was collected from Rhododendron Flats in Manning Park B.C. and stored at 3°C until required. Samples of new (less than 4 months old) and old (more than a year old) foliage, male and female WSBW pupae and adults of both sexes were collected from each rearing regime and freeze dried.

A subset of larvae were assigned randomly to one of the four rearing regimes and reared individually through their fifth and sixth instars. Weight measurements were taken within 24 hours of moulting. Adults were allowed to mate in pairs, egg counts were made, and percentage hatch determined.

Samples for XES analysis were mixed with Somar Mix^{4/} in a ratio of 2 parts sample: 1 part Somar-Mix and thoroughly ground in a SPEX^{5/} mill for five minutes. Two 60 mg self-supporting 13 mm diameter pellets were made in a KBr die at a pressure of 1000 kg. Quantitative programs were developed using standard addition techniques on bulked DF foliage and female WSBW material. Checks were made against U.S. National Bureau of Standards (NBS) orchard leaves (# 1571) and NBS bovine liver (# 1577).

All XES analyses were carried out by irradiating each pellet with Mo-filtered X-rays produced by a Mo X-ray tube at 35 keV and 0.2 Ma for 400 sec. The count rate of the emitted X-rays was 20K cps and they were detected by a

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^{4/} Somar Laboratories Inc., New York, N.Y.

^{5/} SPEX Industries Inc., Metuchen, N.J.

Si-Li drifted detector which had a 185 eV resolution at 5.895 keV. The general apparatus has been described by D'Auria and Bennett (1975).

Three pellets of pure Somar-Mix were also analysed with each group of samples to provide an average "background" spectrum. This was proportionalized to the analyte spectrum and subtracted to produce a spectrum with a minimum of background. Regions of interest were defined on this background subtracted spectrum to obtain the number of counts for each element being considered. Each region of interest was expressed as a proportion of the Compton backscatter peak (before background subtraction) of the analyte spectrum for derivation of the quantitative proportionalities. A detection limit was assigned at the point where the negative confidence interval ($P = 0.05$) of the calibration curves intersected the X-axis, i.e. the point where the normalized variable computed from the XES spectrum was equal to the confidence interval.

Samples of artificial medium, new and old foliage, pupae and adults of both sexes from each rearing regime were analysed for K, Ca, Mn, Fe, Cu, Zn, Br, As, Rb and Sr. An additional experiment was carried out to determine if these same elements were equally distributed between egg masses and the residual body of female WSBW from the AM rearings. For this study one group of five samples of five

females each were freeze dried and analyzed to determine the overall ppm of each element. In a second group, five samples of five females each were taken, anaesthetized with CO₂, the ovaries and associated tissues removed from abdomens and the composited samples of the five egg masses and five residual carcasses freeze dried prior to XES analysis.

Comparisons of elemental data among life stages, and among whole insects, egg masses, and skeletons, were carried out using ANOVA in ^{6/}MIDAS. Stepwise discriminant analysis, BMD: P7M (Jennrich and Sampson 1977), was used to test whether the elemental profiles of the insects reared from each host foliage and the artificial medium were distinct.

Results and Discussion

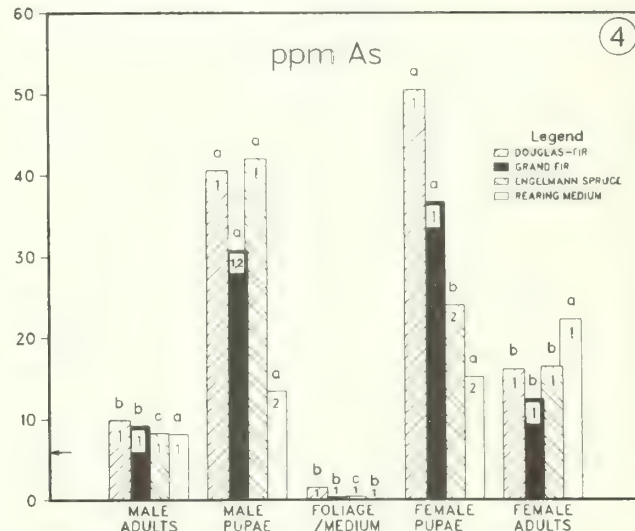
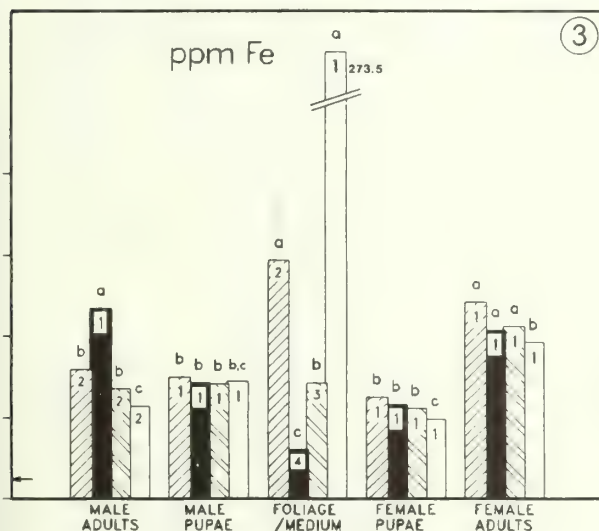
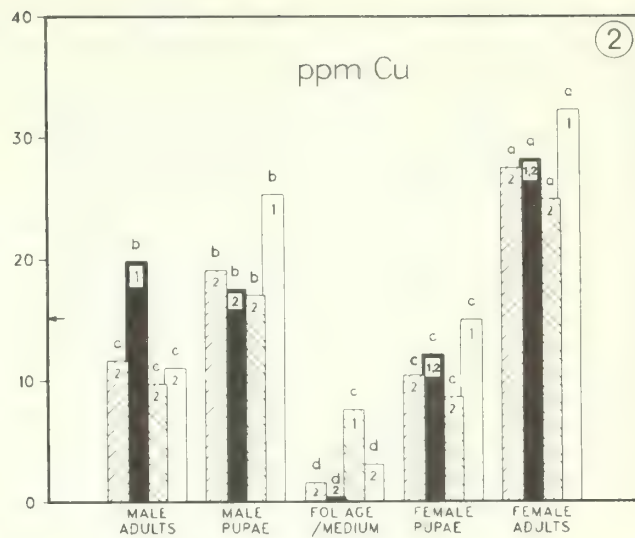
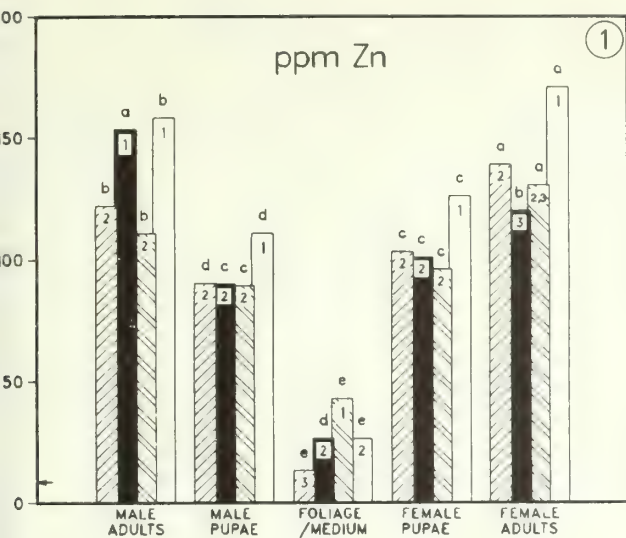
The WSBW feed primarily on new foliage. They are voracious feeders and the majority of their consumption of foliage occurs during the fifth and sixth instars (Brown 1973). During

^{6/}Michigan Interactive Data Analysis System (Fox and Guire 1976).

TABLE I: Comparison of elemental levels in new and old foliages of the Douglas-fir, Engelmann Spruce and Grand Fir, used to rear the WSBW

Element	ppm ^{a/}					
	Df		ES		GF	
	Old	New	Old	New	Old	New
K	4106b	7300a	5800b	17000a	5000b	11400a
Ca	9700a	5017b	12706a	2103b	10145a	6100b
Mn	104.0a	80.3b	540.4a	124.8b	593.7a	244.1b
Fe	99.8a	58.6b	202.5a	28.6b	34.0a	12.1a
Cu	0.2a	1.6a	10.0a	7.6a	2.6a	0.4a
Zn	4.9a	13.2a	69.4a	42.9b	24.2a	26.4a
As	6.5a	1.5a	4.3a	0.4a	2.4a	0.3a
Br	18.0a	10.4a	10.8a	15.0a	7.4a	7.1a
Rb	5.5a	7.9a	7.0b	11.6a	9.2b	22.3a
Sr	53.7a	24.8b	82.4a	15.2b	50.6a	28.4b

^{a/}Means within each element by host category followed by the same letter not significantly different, t-test, $P < 0.05$



FIGURES 1-4: Results of the study showing levels of elements in western spruce budworm pupae and adults reared from three host foliages and artificial medium.

NOTE: Letters above bars indicate significant differences among life stages reared on each host; numbers within bars indicate significant differences within the same life stages taken from each rearing regime, Scheffe's Test, $P < 0.05$; detection limit indicated by horizontal arrow on Y-axis.

this period, tremendous growth takes place. For these reasons it was assumed that there would be sufficient opportunity for the different food sources to produce an effect on the elemental profile of reared pupae and adults. There were wide differences in element concentrations between new and old foliage with higher concentrations of K in all new foliages and higher Rb levels in new foliage for ES and GF. There were lower concentrations of Ca, Mn, Fe (except for GF) and Sr in new foliage as compared to old foliage (Table I). The remaining elements (Cu, As, Br) did not vary in concentration between old and new foliage except Zn which showed a minor variation with higher levels in old ES foliage.

Two of the important enzyme co-factors in living tissue, Zn and Cu, showed elevated levels in WSBW pupae and adults as compared to the new foliage (Figs. 1, 2). Even though ES foliage had the highest Zn levels amongst the foliages and AM, it was the insects reared on the artificial medium which had highest levels. Zn levels were similar in male and female pupae but there was considerable variation among the adults (Fig. 1). A similar pattern of increasing Cu levels was found from new foliage to female pupae and female adults. Although Cu levels of male pupae were elevated, they decreased during metamorphosis to the adult (Fig. 2). No explanation can be given for this phenomenon. It should also be noted that neither the oxidation state nor the chemical

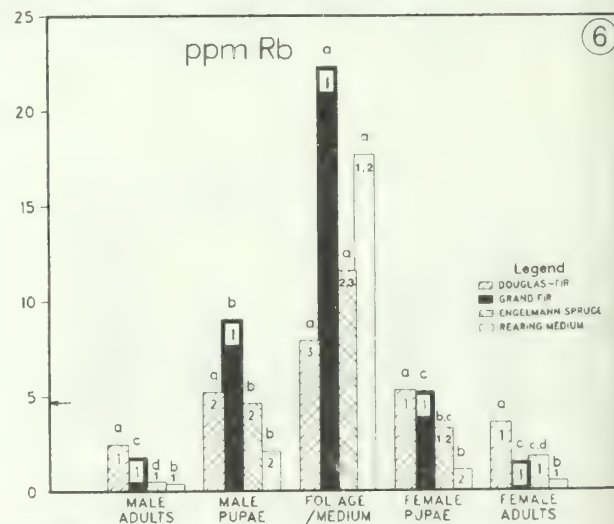
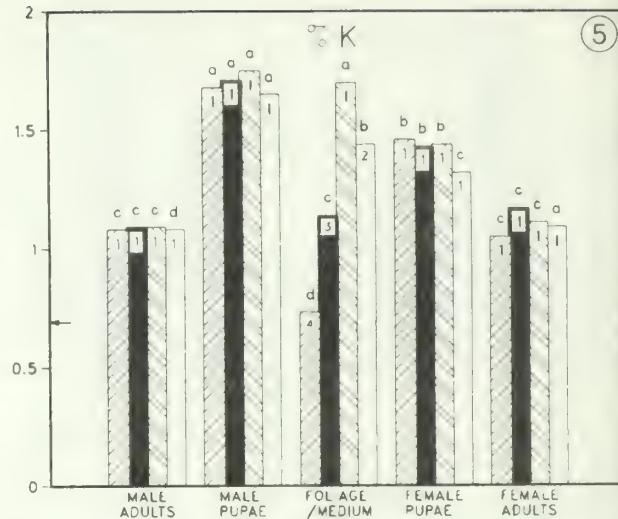
environment of the element in the insect is determined during XES analysis. Levels of Fe varied widely among foliages and artificial medium but all pupae had similar concentrations (Fig. 3). Adults also had similar levels except GF male WSBW reared on GF which had higher Fe levels than other males. These results suggest that Fe is probably under homeostatic regulation.

Highly variable levels of As were found in the insect life stages even though concentrations in the foliage and AM were extremely low (Fig. 4). Accumulations of these high levels suggest bioaccumulation may have occurred in the field before the laboratory rearing was undertaken. There was a significant decrease in As concentrations in the emerged adults.

Levels of the important macronutrient K were significantly different among the rearing medium and new foliages (Fig. 5). The levels within each life stage were not significantly different, suggesting that this element is also under homeostatic regulation. Levels in adults were significantly less than those of the pupae. A potassium substitute of some interest is Rb and it has been used as a marker element for dispersal studies (see recent review by Raulston 1979). The levels of Rb in the foliages and AM were relatively low and there were decreasing levels recorded in pupae and adults (Fig. 6).

The elements Ca and Sr were present in comparatively high concentrations in the foliages and artificial medium but only small amounts were taken up by the insects (Figs. 7, 8). Br levels, on the other hand, have undergone bioaccumulation, especially in those insects reared on DF and GF (Fig. 9). It is possible that salt spray accumulated on foliage samples collected from the University Endowment Lands and that once Br was within the larvae it was not excreted. Of all the elements, Mn was one of the most abundant in foliage samples but was barely detectable in the WSBW life stages (Fig. 10). It would appear that this element is either not taken up or is rapidly excreted by the WSBW.

How was the development of the WSBW affected by the various diets? The larvae which fed on the artificial medium showed greater weight gains in the females at all life stages (Table 2). There were no significant differences in weight gain (as a proportion of L6 weight) for male pupae or adults (Table 2) among food sources. The numbers of eggs laid by females reared on the host foliages were similar although significantly fewer eggs were laid by females reared on AM. Percentage hatched was also significantly greater for the eggs from the three host foliage reared females (Table 2). These results suggest that mating may not have been successful for the insects reared on artificial medium.



FIGURES 5-6: Results of western spruce budworm rearing study showing variations in elemental concentrations among host foliages and insect life stages. See note on Figs. 1-4 for explanation of significance levels indicated.

TABLE 2: Summary of development data for field collected western spruce budworm reared on new foliages of three host tree species and artificial medium

Stage ^{b/}	Males				Females			
	DF ^{a/}	ES	GF	AM	DF	ES	GF	AM
Live weight (mg)								
Initial L6 weight (No.)	25.3 (6)	40.4 (4)	46.3 (5)	31.1 (4)	40.5 (3)	66.9 (6)	54.0 (6)	41.7 (7)
Live weight as a proportion of L6 weight								
Initial pupal weight	2.9a	2.5a	1.8a	3.0a	1.9b	2.2b	1.9b	5.0a
Final pupal weight	2.5a	2.0a	1.5a	2.6a	1.6b	2.1b	1.7b	4.4a
Adult weight	1.5a	1.5a	0.8a	1.5a	1.2b	1.4b	1.2b	3.4a
Fecundity (eggs per female) (n)					120.8ab (10)	143.3a (9)	102.8ab (9)	68.4b (9)
Mean percent hatch					98.6a	91.2a	89.4a	32.1b

^{a/} Hosts indicated as DF = Douglas-fir, ES = Engelmann Spruce, GF = Grand Fir and AM = artificial medium.

^{b/} Weights determined within 24 hours of moulting to minimise variation resulting from feeding.

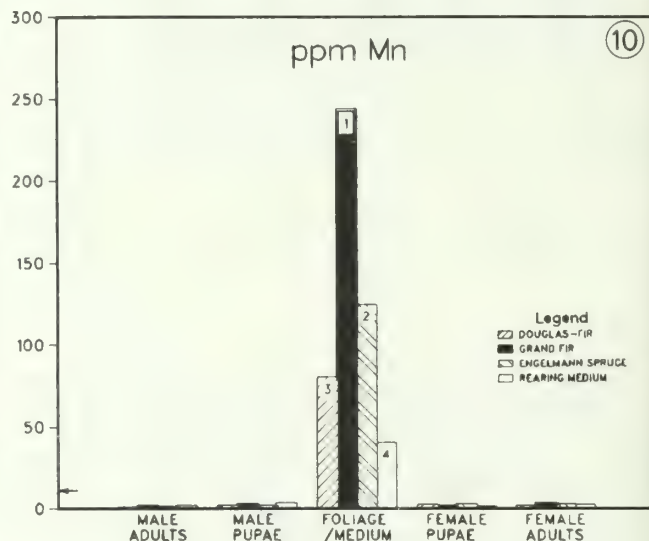
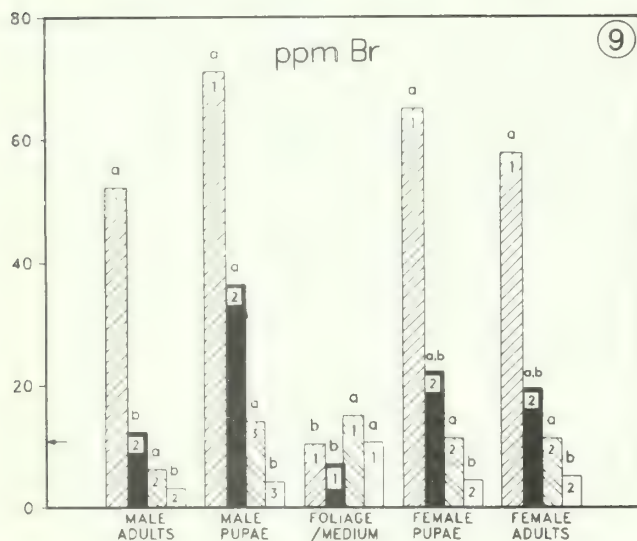
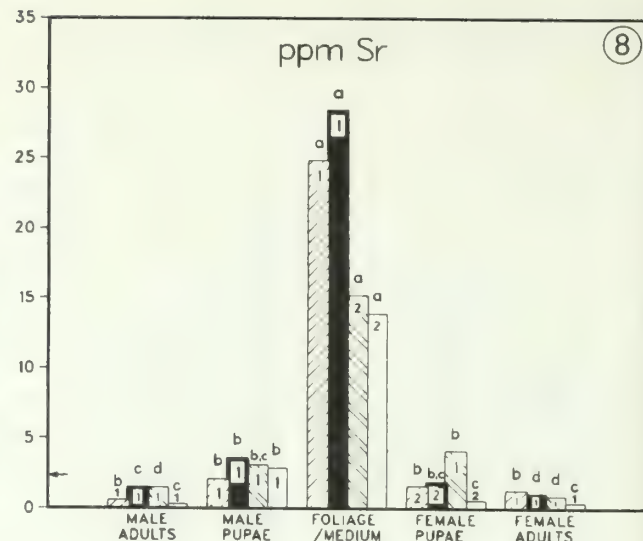
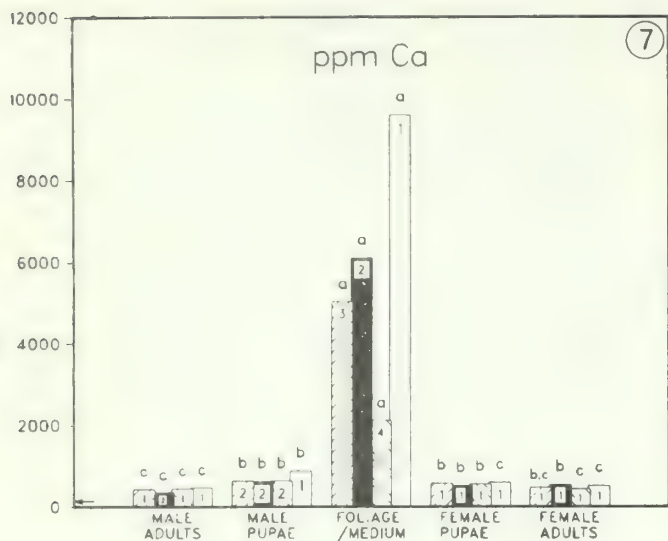
Comparisons of the levels of Fe, Cu, and Zn in carcasses and egg masses showed higher Fe and Cu levels in the carcasses and higher Zn levels in the egg masses (Table 3). Thus, the amount of oviposition by females will affect residual levels of these elements which could be of consequence in population studies of female WSBW involving chemoprinting. Fluctuations associated with oviposition or feeding may be circumvented by using a portion of the body not associated with oviposition such as a wing as Turnock *et al.* (1980) suggested in their study of the red turnip beetle, *Entomoscelis americana* Brown. In retrospect a more reliable chemoprint for female WSBW might be obtained by removing abdomens before analysis.

In the discriminant analysis of males from the four rearing regimes, 16/17 (94%) were correctly assigned to their feeding group in the jackknife classification procedure (Table 3). All group means were significantly separated from each other. For the females, the problem of partitioning Zn, Fe and Cu between carcasses and egg masses was allowed for by designating these elements a "secondary" set in the discriminant analysis. This required that selection of significant variables be made from among the other seven elements first and only when none of these met the criterion for entry ($F = 4.0$) would selection be made from the secondary set. In this case, the results were identical with and

TABLE 3: Comparisons of Fe, Cu and Zn levels in whole insects, egg masses and residual carcasses of WSBW reared on artificial medium

Element	ppm ($\bar{x} \pm s.d., n=5$) ^{a/}		
	Whole Insect	Skeleton	Egg Mass
Fe	27 \pm 3b	49 \pm 5a	20 \pm 5c
Cu	12 \pm 3b	22 \pm 7a	7 \pm 4b
Zn	153 \pm 9ab	132 \pm 18b	168 \pm 31a

^{a/} Means within rows followed by the same letter, not significantly different, $P < 0.05$, Scheffe's Test.



FIGURES 7-10: Results of the study showing levels of elements in western spruce budworm pupae and adults reared from three host foliages and artificial medium. See note with Figs. 1-4 for explanation of significance levels indicated.

without the designation of a secondary set of elements with only Zn and Br being included in the discriminant function. The only group means not statistically distinct were those of female WSBW reared on the ES and GF. (Table 5). In the jackknife classification procedure only 11/18 (61%) of the females were correctly assigned to rearing regime.

House (1974) reviewed the roles of minerals in insect nutrition tabulating data for Ca, Cu, Fe, K and Zn (of the elements considered in this study). He also described the area of mineral requirement of insects as probably the most neglected area of research in insect nutrition.

Quantitative multi-elemental procedures, such as XES, will add greatly to our understanding of normal element concentrations and allow us to more fully appreciate the normal homeostatic mechanisms operating during an insect's metamorphosis and will also, hopefully, indicate which elements are suitable for geographical characterization of populations. Three promising candidates appear to be As, Br and Rb. Some of these, especially Rb, might be manipulated to mark a forest defoliator population, as has been done with several agricultural insects (Raulston 1979). More reliable chemotyping results for female WSBW might be obtained by removing abdomens prior to analysis and by so doing avoid variations related to oviposition.

TABLE 4: Results of discriminant analysis of male adult WSBW reared on Douglas-fir, Grand Fir and Engelmann Spruce foliages, and artificial medium (DF, GF, ES and MED respectively)

Step Variable Entered	Coefficients for Canonical Variable		Element
	1	2	
1	-0.21	0.22	Br
2	0.12	-0.06	Fe
3	0.11	0.06	Zn
Constant	-11.18	-0.18	

Eigenvalues: 7.82, 6.78

Cumulative proportion of total dispersion: 0.47, 0.88

Canonical Correlations: 0.94, 0.94

Matrix of F-values for testing group means:

Group	DF	GF	ES
GF	15.09**		
ES	27.30**	10.72**	
AM	23.20**	24.54**	24.20**

Jackknife classification matrix:

Origin of	No. Classified as				Total
	DF	GF	ES	AM	
Moths					
DF	5	0	0	0	5
GF	0	4	1	0	5
ES	0	0	5	0	5
AM	0	0	0	2	2

61.1% of calibration group correctly assigned to host food source.

Probability level indicated, ** = $P < 0.01$

Acknowledgements

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TABLE 5: Results of discriminant analysis of female adult WSBW reared on foliage from Douglas-fir, Grand Fir, Engelmann Spruce and artificial medium (DF, GF, ES and AM respectively)

Step Variable Entered	Coefficients for Canonical Variable		Element
	1	2	
1	-0.08	0.03	Zn
2	0.01	0.07	Br

Constant 11.15 -5.47

Eigenvalues: 3.35, 2.40

Cumulative proportion of total dispersion: 0.58, 1.00

Canonical Correlations: 0.88, 0.84

Matrix of F-values^{a/} for testing group means:

Group	DF	GF	ES
GF	11.38**		
ES	13.08**	0.96	
AM	17.65**	18.43**	13.03**

Jackknife classification matrix:

Origin of	No. Classified as				Total
	DF	GF	ES	AM	
Moths					
DF	2	1	1	0	4
GF	1	3	0	0	4
ES	2	1	2	0	5
AM	1	0	0	4	5

61.1% of calibration group correctly assigned to host food source.

^{a/} Probability level indicated, ** = $P < 0.01$

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The epicuticular waxes from four host
nts of the eastern spruce budworm are
mined with respect to their influence
the feeding behavior of the sixth-
tar larva. Both current and one-year
needles contain stimulating chemicals
their epicuticular wax layer. Some
e fatty acids known to occur in balsam
wax are stimulatory, and may serve to
ance the already strong feeding
ponse to sucrose.

roduction

The feeding responses of eastern
uce budworm larvae toward various pure
micals and some extracts from white
uce were first studied by Heron (1965).
ir responses to polar and non-polar
ounds from a number of evergreen
nts were studied by Albert and Jerrett
81) who showed that the sugar/glycoside
ction from balsam fir was more
mulating than either amino acids or
anic acids from the same host.
sequently, Albert et al. (1982)
racterized the feeding responses to
e carbohydrates, and reported that
ose was the most stimulating of the
ars tested. Sucrose is known to play
important role in the feeding behavior
many insects (Dethier, 1966). In
uce budworm larvae, the peak response
sucrose is in the range from 0.01 to
5M, with a behavioral threshold at
4 to 10^{-3} M, indicating a high degree
ensitivity to this chemical (Albert
al., 1982).

Using four of the more common host
cies in eastern North America (balsam
white, black and red spruces), Albert
83) found that the sugars/glycosides
n all four hosts were highly
mulating to spruce budworm larvae.
e acids were only slightly stimulating
e organic acids were neutral or
urrent. Lipids from white and red
uces were more stimulating than those

from balsam fir and black spruce. This
fraction from white spruce was found to be
even more stimulating than the sugars/
glycosides.

The first stage in the feeding
behavior of many phytophagous insects
involves the "test biting" of the leaf
surface, a process which may be initiated
as a result of the stimulation of
peripheral sensilla by material contained
in the epicuticular wax layer of the
plant leaves (Bernays et al., 1975).
Simple observations in our laboratory
showed that a larva crawling on the
surface of a fresh shoot of balsam fir
would palpate the surface of the foliage
with its maxillae, and bite into the leaf
within a few seconds. Larvae given foliage
treated with hexane to remove the
epicuticular waxes spent considerable time
palpating the surface without biting. The
present study examines the feeding
responses of spruce budworm larvae to
surface chemicals from four host plants
and to some pure fatty acids known to
occur in balsam fir wax (Berl and Lemon,
1970).

Materials and Methods

Sixth-instar larvae were used in two-
choice tests as described previously
(Albert et al., 1982). Control discs were
impregnated with 15 μ l of hexane which was
allowed to evaporate. They were then
wetted with 15 μ l of distilled water. Test
discs were impregnated with 15 μ l of a
solution of epicuticular waxes in hexane.
The solvent was allowed to evaporate and
the discs were then wetted with 15 μ l of
distilled water.

Extracts of epicuticular waxes were
obtained from balsam fir (Abies balsamea),
white spruce (Picea glauca), black spruce
(Picea mariana), and red spruce (Picea
rubens). These were prepared by dipping
10g of "fresh" needles (from frozen
samples which were collected on June 14,
1982 from the Acadia Forest Experiment
Station, N.B.) in 200 ml of glass-
distilled hexane for 30 sec. The solvent
was evaporated and the extracted material
was re-dissolved in 3 ml of hexane to
provide the stock solution for the
behavior tests.

Some fatty acids were tested at a
concentration of 10^{-3} M. Those which proved
stimulating were further tested in
combination with sucrose (0.025M), using
0.025M sucrose on the control discs.

Data are presented either as mean %
consumption (\pm S.E.) of test versus control
discs, or as a preference index ($PI = (T - C) / H$),
where PI is the preference index, T is the

amount eaten of the test discs, C is the amount eaten of the control discs, and H is the time in hours). Multiplying the PI by 33.183 yields the difference in disc area (mm²) eaten between test and control discs per hour.

Results and Discussion

The feeding preferences for discs containing extracts of epicuticular waxes from host plants versus control discs are shown in Figure 1. All four hosts' waxes contain stimulatory chemicals which presumably serve as biting stimuli.

FIGURE 1. MEAN % CONSUMPTION (+ S.E.) OF DISCS TREATED WITH HEXANE EXTRACT AND WITH WATER IN TWO-CHOICE TESTS.

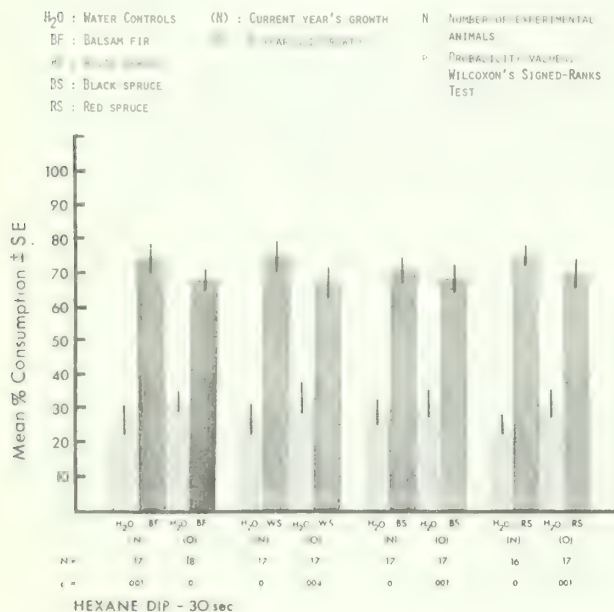
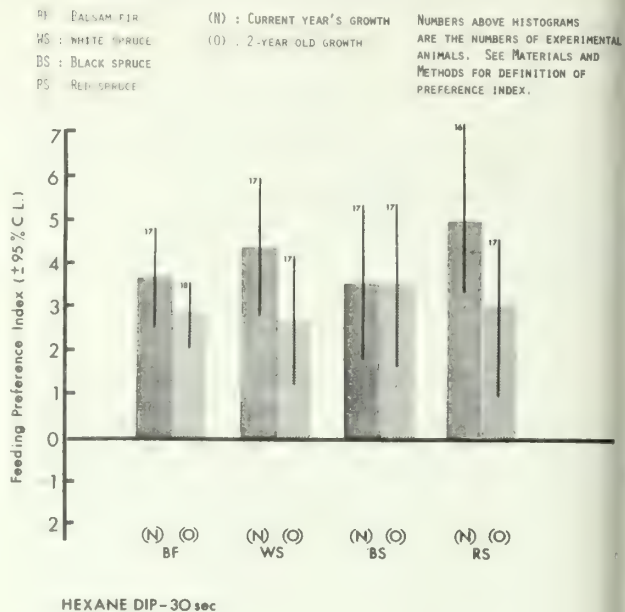


Figure 2 shows the Preference Index values for each host. In general, greater feeding occurs on discs treated with epicuticular waxes from the current year's growth from all hosts except black spruce where new and old needle waxes produce the same results. Red spruce shows the highest Preference Index followed by white spruce, then balsam fir and black spruce. The most significant finding for these tests is that the epicuticular waxes from all hosts, for both old and new needles, not only induce biting by larvae, but they also contribute to the maintenance of feeding though at a reduced level compared to sugars and glycosides (Albert, 1983; Fig. 2).

FIGURE 2. FEEDING PREFERENCE INDEX FOR ANIMALS IN TWO-CHOICE TESTS USING HEXANE EXTRACTS FROM NEW OR OLD FOLIAGE FROM FOUR HOST PLANTS.



A preliminary separation of the epicuticular waxes from balsam fir and white spruce current year's foliage was performed using gas chromatography and mass spectrometry techniques by Dr. A.P. Tulloch (Prairie Regional Lab, N.R.C., Saskatoon). The weights of purified materials recovered for each host are presented in Table 1. To date, the first three fractions from balsam fir have been tested, and each shows strong feeding stimulant activity. These contain hydrocarbons as well as esters.

Since pure fatty acids contained in the epicuticular wax from balsam fir are known (Berl and Lemon, 1970), we tested these at a concentration of 10^{-3} M. The results are shown in Table 2. Lauric, myristic, oleic, linoleic, linolenic, lignoceric, and palmitoleic acids all stimulate feeding. To test whether these could synergize with sucrose, a known feeding stimulant, tests with fatty acid and sucrose combinations were performed. Results are shown in Table 3. Myristic, oleic, and palmitoleic acids all enhance the feeding response to sucrose alone, with oleic acid having the greatest effect.

Some fatty acids which were not stimulating by themselves were also tested in combination with sucrose. Palmitic and heptadecanoic acids were shown to also increase the feeding response to sucrose (Table 4).

I. CHEMICAL FRACTIONS RECOVERED FROM EPICUTICULAR WAXES
BALSAM FIR AND WHITE SPRUCE, HEXANE DIP, 30 SEC, CURRENT
EEDLES,

fir.
weight: 0.340 g

Weight	Comments on composition
0.0113	Hydrocarbons (considerably contaminated)
0.0500	Methyl esters C ₂₂ -C ₃₄ ; Esters of hexanol (and octanol) C ₃₂ -C ₄₄ . Numerous uniden- tified components but no aldehydes detected (difference from white spruce)
0.0720	Mostly di(2-ethylhexyl) phthalate (contaminant) and some esters
0.0110	Phthalate ?
0.0450	10-nonacosanol
0.0460	Some free acids C ₂₂ -C ₃₀ and small amount of C ₃₂ -C ₃₆ triacyl glycerols
0.0210	Small free alcohols C ₁₈ -C ₃₀
0.0700	
0.0800	Small diols (C ₂₉ like those in Juniper wax)

ons 8 to 11 also contain numerous unidentified components,
ly diterpene acids and probably appreciable amounts of
sters (estolides) which are always found in conifer waxes.

spruce.
weight: 0.196 g

0.0060	Hydrocarbons (considerably contaminated)
0.0210	Methyl esters C ₂₂ -C ₃₂ . Esters of hexanol and octanol C ₃₆ -C ₄₂ . Aldehydes C ₂₂ -C ₃₂ . Numerous unidentified components
0.0080	Phthalate ?
0.0050	
0.0120	
0.0450	10-nonacosanol
0.0110	Free acids C ₂₂ -C ₃₂
0.0730	Acids C ₁₆ -C ₃₀ . Alkanols C ₂₂ -C ₂₈ . Diols

otnote to balsam fir composition.

compliments of Dr. A.P. Tulloch, NRC Prairie Regional Lab,
oon, Saskatchewan. GC-Mass Spec. separations.

MEAN % CONSUMPTION OF DISCS TREATED WITH WATER (CONTROL)
H FATTY ACIDS IN TWO-CHOICE TESTS

(H ₂ O)	FATTY ACID (10 ⁻³ M)	N	P
7)	41.5 (3.7) CAPRIC	17	0.026
7)	66.3 (3.7) LAURIC	14	0.002
9)	63.6 (2.9) MYRISTIC	18	0
0)	45.8 (5.0) PENTADECANOIC	14	0.510
6)	41.6 (4.6) PALMITIC	15	0.045
4)	43.4 (5.4) STEARIC	17	0.266
8)	65.3 (2.8) OLEIC	17	0.001
0)	58.6 (3.0) LINOLEIC	18	0.019
6)	61.4 (3.6) LINOLENIC	17	0.015
9)	53.7 (2.9) ARACHIDIC	16	0.211
4)	51.3 (3.4) BEHENIC	18	0.542
5)	64.6 (3.5) LIGNOCERIC	18	0.002
0)	64.4 (3.0) PALMITOLEIC	17	0.002
8)	55.3 (3.8) HEPTADECANOIC	18	0.136

of experimental animals

probability values, Wilcoxon's Signed-Ranks Test

TABLE 3. MEAN % CONSUMPTION OF DISCS TREATED WITH SUCROSE (0.025M)
AND WITH A COMBINATION OF SUCROSE AND FATTY ACID IN TWO-CHOICE TESTS

MEAN % CONSUMPTION (±S.E.)				
CONTROL SUCROSE (0.025M)	0.025M SUCROSE +FATTY ACID (10 ⁻³ M)		N	P
45.1 (2.6)	54.9 (2.6) LAURIC		19	0.084
38.8 (2.7)	61.2 (2.7) MYRISTIC		20	0.002
32.4 (3.0)	67.6 (3.0) OLEIC		16	0.001
48.6 (2.3)	51.4 (2.3) LINOLEIC		17	0.813
46.7 (2.6)	53.3 (2.6) LINOLENIC		18	0.246
46.5 (3.2)	53.5 (3.2) LIGNOCERIC		16	0.281
40.8 (3.1)	59.2 (3.1) PALMITOLEIC		18	0.012

N= Number of experimental animals

P= probability values, Wilcoxon's Signed-Ranks Test

TABLE 4. MEAN % CONSUMPTION OF DISCS TREATED WITH SUCROSE (0.025M)
AND WITH A COMBINATION OF SUCROSE AND A FATTY ACID IN TWO-CHOICE TESTS

MEAN % CONSUMPTION (±S.E.)				
CONTROL SUCROSE (0.025M)	0.025M SUCROSE +FATTY ACID (10 ⁻³ M)		N	P
47.9 (3.9)	52.1 (3.9) CAPRIC		16	0.638
42.7 (3.2)	57.3 (3.2) PENTADECANOIC		14	0.056
41.3 (2.6)	58.7 (2.6) PALMITIC		20	0.002
46.9 (2.9)	53.1 (2.9) ARACHIDIC		19	0.420
55.2 (3.2)	44.8 (3.2) BEHENIC		17	0.136
39.9 (3.5)	60.1 (3.5) HEPTADECANOIC		16	0.005

N= Number of experimental animals

P= probability values, Wilcoxon's Signed-Ranks Test

Epicuticular waxes are obviously of some importance in the feeding behavior of eastern spruce budworm larvae. They are the first gustatory chemicals which the insect encounters while palpating the surface of the leaf prior to biting and feeding. It is reasonable to assume that some of the chemicals serve to trigger the "test bite" response. However, their role may be much more important in serving to enhance the feeding response to the polar and non-polar compounds present within the leaf sap. The exact nature of this effect remains to be examined in greater detail both by behavioral and by electro-physiological techniques. More importantly, a study of the effects of epicuticular waxes on the feeding behavior of second- and third-instar larvae may shed some light on their possible role in stimulating these early instars to establish feeding sites on the developing buds. It is at this stage that a feeding or biting deterrent would likely be most effective in preventing larvae from establishing themselves on a host plant.

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CHORISTONEURA FUMIFERANA (CLEM.)

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Extracts of non-host plants and selected naturally occurring compounds have been screened for their effects on feeding by spruce budworm larvae, (Choristoneura fumiferana (Clem.)), using as diet a filter paper substrate impregnated with the synergistic feeding stimulants, sucrose, and L-proline. The most potent feeding deterrents identified to date are alkaloids.

A simple, fast and reproducible feeding assay for spruce budworm larvae, (Choristoneura fumiferana (Clem.)), was described by Bentley, Leonard, and Mott (1979).

For the assay, sixth-instar larvae are induced to feed on a filter paper substrate impregnated with the synergistic feeding stimulants sucrose and L-proline. Frass resulting from ingestion of this material is readily recognizable, and counts of frass pellets provide an indication of the quantity consumed. The effects on feeding of adding plant extracts and test chemicals to the substrate can thus be investigated readily. Its simplicity, speed, and modest requirements for test material make this assay suitable for mass screening, and it has, to

date, been used to test more than 110 non-host plants, as well as about 60 naturally occurring chemicals, for their effects on budworm feeding.

An analysis of the results, published recently (Bentley et al. 1982), reveals that although none of the plants tested is a normal host of spruce budworm larvae, only six extracts displayed activity in the category designated "highly deterrent". All plants belonging to the most active group are known to contain alkaloids, and, in each case, the greatest activity was found to be localized in the basic fractions. Among the pure alkaloids tested, including representatives of the pyrrolizidine, solanum, quinolizidine, berberine, and strychnos groups, fewer than 25% were "highly deterrent" at the concentrations assayed.

Recent research has been directed to a "fine-tuning" of the bioassay, to provide greater sensitivity and allow more protracted observation of the effects on larvae of the test compounds. In addition, further screening is planned in an attempt to identify potent feeding deterrents with minimal toxic properties. A study of the structure-activity relationships which have begun to emerge may prove to be a profitable direction for future research.

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¹ Paper presented by this author.

AGE CONSUMPTION BY 6TH-INSTAR SPRUCE BUDWORM
AE, *CHORISTONEURA FUMIFERANA* (CLEM.), FEEDING
BALSAM FIR AND WHITE SPRUCE

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Female larvae ate about 1.5 times as much
age as male larvae. Larvae ate significantly
old foliage than current foliage. Balsam
current foliage was eaten in greater
tities than any other foliage; white spruce
ent and balsam fir old were eaten to the same
nt; very little old white spruce was eaten.

roduction

To model the effect of budworm larval
ity on loss of fibre production in balsam fir
white spruce, data on the amount of current
old foliage consumed by larvae are required.
e paper summarizes the work, to date, on the
inuing study.

aterials and Methods

Field-collected branches of each host
ies were trimmed to the current year's
wth attached to the apical 4 cm of the
vious year's growth from which all needles had
removed. Other shoots were trimmed to 1-yr-
foliage attached to 4 cm of the previous
's growth. About 250 such shoots were
pared from any one tree at any one time. Each
ot was placed in water overnight. The
lowing day, surface water was removed from the
a and the shoot was weighed. Shoots that had
ced overnight were discarded. Each shoot was
ced in a numbered screen-topped cup with the
e of the shoot projecting through a hole in
bottom of the cup and into water. One newly-
ated, i.e., less than 8 h old, unfed 6th-
lar larva was placed in each cup with one
ot. Approximately 100 males and 100 females
e used for each experiment. The remaining 50
ots were used to construct a standard curve
ating foliage dry weight to fresh weight.
se shoots were oven-dried at 65°C when 50% of
larvae had pupated. The standard curve was
l for predictive purposes.

The experiments were carried out in a room
26°C, 80% RH, and a 16 h photoperiod. As each
va pupated, the pupa was placed in a glass
and the shoot was oven-dried.

The dry weight of the shoot offered to each
larva was predicted from a regression of dry
weight on fresh weight, i.e., from the standard
curve. The ovendry weight of the shoot at the
end of the larval feeding period was subtracted
from the predicted original dry weight. The
difference in dry weights was an estimate of the
amount eaten.

The frass produced by each 6th-instar larva
was oven-dried and weighed. After 24 h, emerged
moths were killed, oven-dried, and weighed.

Results and Discussion

Standard Curves

The correlation coefficient between dry
weight and fresh weight of foliage was very high
for both current and old foliage; 10 standard
curves for balsam fir ranged between 0.903 and
0.997 and averaged 0.977; 6 curves for white
spruce ranged between 0.972 and 0.999, averaging
0.990. However, the standard errors and
consequently the 95% prediction limits about the
mean of a new sample were too high for the dry
weight of a single shoot, or even small samples,
to be predicted with sufficient accuracy. For
example, the standard errors, for different
sample sizes, of predicted mean dry weight for
balsam fir current year foliage having a mean
fresh weight of 3.64 g were obtained from the
following regression

Dry weight (mg) = 31.06 + 308.41 fresh weight (g)
 $r = 0.99$, $n = 51$, $Sy.x = 4683.9$

Sample size	Standard error, mg
5	32.6
10	24.4
20	19.0
40	15.7
80	13.7

Because the proportion of water present in
current year shoots drops continuously during the
growing season, a standard curve had to be
developed for each experiment. When 6th-instar
larvae first appear in the field, the water
content of the current year shoots is 80-85%, by
the end of the growing season it is 55%, and in
1-yr-old foliage water content is 49%.

Foliage Consumption

The data from four experiments using balsam
fir current year foliage were pooled, and similar
data from four experiments using balsam fir old
foliage were pooled. The average amount of
current foliage consumed by a 6th-instar female
larva ($n = 203$) was 315 mg dry weight, for males
it was 207 mg ($n = 174$). For old foliage the
average figures were 201 mg ($n = 95$ females) and
128 mg ($n = 139$ males). This reduction in

consumption associated with old foliage affected both males and females to the same extent, about 38%. Females ate 1.52 as much current foliage and 1.57 as much old foliage as did males.

The above statistics refer to larvae that eventually emerged as moths. During the study, some pupae died. Females that died in the pupal stage consumed an average of only 211 mg of current fir foliage whilst males consumed an average of 132 mg.

The data from three experiments using white spruce current year foliage were pooled, and similar data from four experiments using white spruce old foliage were pooled. The average amount of current foliage consumed by a 6th-instar female larva ($n = 152$) was 190 mg dry weight, for males it was 134 mg ($n = 122$). For old foliage the average figures were 92 mg ($n = 108$ females) and 67 mg ($n = 83$ males). As with balsam fir, the reduction in consumption associated with old white spruce affected both males and females to the same extent. However, this reduction in consumption of white spruce, 51%, was greater than the 38% reduction associated with old fir. Females ate 1.42 as much white spruce current foliage and 1.37 as much old foliage as did males.

Females dying as pupae ate, on average, 156 mg of white spruce current foliage whilst males ate 125 mg.

Both male and female 6th-instar larvae eat significantly more balsam fir than white spruce, a difference that holds true for both current and old foliage. As white spruce produces more foliage than balsam fir, the net effect is less defoliation on white spruce, and presumably less fibre loss, if there is approximately the same density of larvae on each tree.

Tree Species and Insect "Performance"

The dry weight of a 24-h-old moth is a convenient measure of an insect's performance. White spruce current year foliage produced the largest moths, males averaged 11.6 mg, females averaged 21.1 mg; followed by balsam fir current year foliage, males 8.2 mg, females 15.3 mg. Balsam fir old foliage produced males which averaged 7.3 mg and females which averaged 11.6 mg. White spruce old foliage gave rise to very small moths; males averaged 2.9 mg and females averaged 4.7 mg.

White spruce current foliage also proved to be the most efficient diet in the sense that the ratio, dry weight of needles eaten:dry weight of moth, was lower than for any other foliage, i.e., 12:1 for males, 9:1 for females. The other foliages were relatively inefficient. Balsam fir old foliage although producing smaller moths than balsam fir current foliage was the next most favorable diet in that the ratios for both males and females were 17:1. Balsam fir current

foliage had a ratio of 25:1 for males and 21:1 for females. White spruce old foliage ratios were 23:1 for males and 20:1 for females.

Because of the problem, with this method, of obtaining sufficient accuracy of the amount eaten, I have been able to deal only with means. For a better understanding of the system it is preferable to use data from individual insects, or trends. An indirect way of looking at consumption is to consider frass production. This has the distinct advantage that the amount of frass produced can be measured without error. It is also reasonable to assume that frass production is representative of the amount eaten. Thus, another way of comparing insect performance on the two hosts is to compare the relationship between moth weight and frass produced by 6th-instar larvae.

Dry frass weight and dry moth weight were correlated and regressions, for comparative purposes, could be defined. For young current shoots of white spruce, collected 31 May 1982, containing 83% water, the regression of frass produced by 6th-instar female larvae on subsequent moth dry weight was

$$\text{Frass (mg)} = 39.37 + 5.010 \text{ moth weight (mg)} \\ r = 0.82, n = 101, \text{Sy.x} = 401.79$$

For similar shoots from the same tree, but collected 15 days later, and containing 71% water, the regression was

$$\text{Frass (mg)} = 39.09 + 8.965 \text{ moth weight (mg)} \\ r = 0.79, n = 17, \text{Sy.x} = 114.43$$

Young current white spruce was the preferred diet in that it produced a moth of a given weight more efficiently than slightly older current foliage, e.g., a female of dry weight 15 mg would have produced 114 mg of frass as a 6th-instar larva feeding on young current shoots, but two weeks later would have produced 174 mg of frass. On average, the ratio of frass weight:moth weight was 6.8:1 for young current foliage and 13.1:1 for older current foliage. A similar trend was seen with males and for both sexes feeding on young and older current year balsam fir needles.

These data confirm the earlier conclusion that current foliage is a preferred diet and they also suggest that such foliage rapidly loses quality. The scenario envisaged for white spruce is that the youngest foliage of the current year is the preferred food, relatively small amounts are required to produce a moth of a certain size as the foliage ages its suitability as a food declines, it is still readily palatable but more of it is required to produce a moth of a certain size; as it ages still further, it becomes unpalatable and larvae eat very little of it.

SPECIES AND FOLIAGE CHEMISTRY

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Feeding efficiencies and growth rates of
ern spruce budworm larvae varied among hosts
ed. Pupae attained normal size regardless
ost species. Candidate defensive compounds
nins and phenols) varied only slightly with
vigor of the host. The relationship between
e defensive compounds and measures of larvae
th were not entirely consistent with current
ries on the role of secondary plant
ounds.

roduction

Within a population of host plants, the
nsity of insect attack and subsequent damage
vary considerably. It is not uncommon for
Douglas-fir, *Pseudotsuga menziesii* var.
ca (Beissn.) Franco, trees near each other
ave quite different populations of western
ce budworm, *Choristoneura occidentalis*
man (McDonald 1981). Western spruce budworm
W) frequently exhibits this preferential
t within and among its hosts in the
hwest.

Numerous explanations for preferential
ck by insects have been suggested including
erences in nutritional values, phenology,
age toughness, host vigor, and plant
nsive compounds. Foliage chemicals have
implicated as specific factors in the
stance-susceptibility characteristics of
las-fir (McMurray 1980). Literature on the
rtant plant defensive compounds has been
uately reviewed by the following authors:
ins (Swain 1979), phenols (Levin 1971, Swain
'), and nitrogen (Mattson 1980).

In this paper we present some preliminary
ults on differences in feeding by WSBW among
important hosts in the Southwest. We also
ort on correlations between WSBW feeding and
entrations of phenols, tannins, and proteins
hite fir, *Abies concolor* (Gord. and Glend.)
l. ex Hildebr., and Douglas-fir foliage.

Methods

Tree Selection

Four hosts of WSBW occurring in northern
Arizona were selected for the feeding
experiments: Douglas-fir, white fir, corkbark
fir, *Abies lasiocarpa* var. *arizonica* (Merriam)
Lemm.; and Engelmann spruce, *Picea engelmannii*
Parry ex Engelm. Trees were selected from mixed
conifer stands approximately 16 km north of
Flagstaff, Arizona, stand elevation
approximately 2,440 meters. These stands had no
recent history of WSBW outbreaks.

Trees suitable for site index determination
were rated for vigor according to Waring et al.
(1980). This technique uses the ratios of the
basal area growth for one-year and five-year
increments to total sapwood area. To obtain
average measurements, four increment cores were
taken at 90° angles from each of 25 trees of
each host species. The increment cores were
then stained with potassium iodide-iodine to aid
in distinguishing the sapwood from the heartwood
(Kutscha and Sachs 1962). Total radius, sapwood
radius, and one- and five-year increment radii
were measured. The ratios were calculated using
this formula:

$$\frac{BA_x}{SA} = \frac{R^2 \pi - (R - r_x)^2 \pi}{R^2 \pi - (R - r_s)^2 \pi}$$

BA_x : basal area of growth increment for
period x

SA : sapwood area

R : total radius

r_x : radius of increment growth

r_s : radius of sapwood

Fifteen trees were selected from the 25
which were cored for each species (five trees in
each of three vigor categories). The five trees
with the highest ratios were classified as high
vigor trees, the five trees with the lowest
ratios were classified as low vigor trees, and
the five trees closest to the mean were
classified as medium vigor trees. The
theoretical range of BA/SA ratio is 1.00 to
0.00. The actual range of BA_5/SA observed for
the four species was: Douglas-fir 0.49 to 0.14,
white fir 0.59 to 0.20, corkbark fir 0.63 to
0.24, and Engelmann spruce 0.60 to 0.13.

Selection of Larvae

Second and third instar larvae were
collected in early May from an ongoing WSBW
outbreak within the Kaibab National Forest,
Arizona. Budworm infested branch tips were
collected from the four host species used in
this study. Larvae were carefully segregated
according to host species; this allowed the
larvae to be fed foliage from the same host

species from which they were collected. The branch tips were placed in Aquapics® to maintain freshness and transported to the laboratory.

The field collected larvae were stored at 2-4°C to slow development until five to seven days before the experiments were to begin. The larvae were then placed at room temperature until they advanced to the fourth instar. Larvae were determined to be in the fourth stadium by head capsule measurements. Bean and Blatzer (1957) and Wagg (1958) were used as guidelines.

Foliage Collection

To standardize the host phenological stage, feeding experiments were begun when the host foliage was determined to be at the "brush" stage (bud cap gone, needles even but no shoot growth so needles appear to arise from one spot) (Shepard unpublished).

We collected paired foliage samples from the midcrown of the host trees at the four cardinal directions. Paired twigs were selected for uniformity in size and phenology. One twig was fed to a budworm, the other twig was used to estimate the average dry weight per needle of the feeding twig. This average dry weight was later used to estimate the dry weight of the foliage consumed by the budworm larva.

Feeding Procedure

The paired twigs were saturated in a 100% relative humidity environment overnight. The following morning the mature foliage was trimmed from the feeding twig. While being held under water, the twig was excised and placed in a water-filled Aquapic®. The prepared foliage was then placed in a paper-lined 150 x 25 mm petri dish.

Fourth instar larvae were weighed fresh and placed on the prepared foliage to feed. Initial dry weight of each larva was estimated using an average percent dry weight of fourth instar larvae. The petri dishes were placed in controlled environmental chambers for the duration of the experiments. Temperature in the chambers ranged from 24 to 26°C; the photoperiod was 16 hours of light and 8 hours of darkness, as recommended by Robertson (1979).

Following each 72 hour feeding period the feeding twigs were removed and replaced with fresh foliage. The number of damaged needles was recorded and the damaged needles still attached to the twig and wasted needles were collected and oven dried at 60°C until no further weight loss occurred. Both wasted and remaining foliage were then weighed on a balance accurate to 0.1 mg. The amount of foliage ingested by each larva was estimated using the following formula:

$$I = (DW \times N) - (W + R)$$

I : foliage ingested

DW: mean dry weight per needle

N : number of needles damaged

W : foliage wasted (clipped but not consumed)

R : foliage remains (damaged but not clipped from the twig)

Each replicate was terminated within 24 hours of pupation. Total foliage ingested was calculated; pupae were sexed and weighed fresh. Feces and pupae were then oven dried at 60°C and weighed.

Nutritional indices were calculated on a dry weight basis according to Waldbauer (1968). The following nutritional indices are used in this study: foliage ingested (I), relative consumption rate (RCR), relative growth rate (RGR), approximate digestibility (AD), and efficiency of conversion of ingested food to body weight (ECI).

Chemical Analysis

Foliage used in the chemical analyses was clipped from the host trees selected for the feeding experiment and immediately frozen for 18 hours at -20°C. Samples were then freeze-dried at -50°C and 50 millitorr in a freeze dryer. Samples were stored at -20°C under dessication until analyzed.

Proteins were analyzed using the Coomassie Brilliant Blue Dye technique (Bradford 1976). Total phenols were determined using the Folin-Denis technique according to Swain and Hillis (1959) and Ribereau-Gayon (1972). Tannins were analyzed using the vanillin reaction assay (Price et al. 1978) as modified by Zucker (unpublished).

Results and Discussion

Comparison of Rearing Methods

The effect of three commonly used rearing procedures on fresh and dry pupal weights was determined for WSBW feeding on Douglas-fir and corkbark fir. Fresh pupal weights were significantly different among rearing methods for corkbark fir but not for Douglas-fir (Table 1). For corkbark fir, fresh pupal weights were significantly higher for insects bagged on foliage in the field than for insects fed excised foliage in the lab. Excised foliage and bagged foliage tests were conducted on the same trees and crown positions. Fresh pupal weights were not significantly different between insects reared on excised foliage and insects that developed under normal field conditions for either host species. Dry weights of pupae were not significantly different between rearing methods (Table 2).

1. Fresh pupal weights of female western spruce budworm by rearing method and host species. a/

REARING METHOD	DOUGLAS-FIR	CORKBARK FIR
COLLECTED	70.6 (5) <u>b/</u>	69.0 (5) A <u>2/</u>
BAGGED	91.6 (4)	83.6 (6) B
COLLECTED	70.5 (77)	59.8 (51) A
	0.1390	0.0014

weights in milligrams.

Numbers in parentheses are number of cases. One-way ANOVA, LSD multiple range test, $\alpha = 0.10$, values followed by different letters are significantly different.

2. Oven-dry pupal weights of female western spruce budworm by rearing method and host species. a/

REARING METHOD	DOUGLAS-FIR	CORKBARK FIR
COLLECTED	20.8 (5) <u>b/</u>	19.2 (5)
BAGGED	16.4 (4)	18.7 (6)
COLLECTED		
	0.4705	0.8974

One-way ANOVA, $\alpha = 0.10$, LSD multiple range test, values followed by different letters are significantly different. Numbers in parentheses are number of cases.

The technique of excising foliage for feeding experiments may lead to misleading results if inducible defensive mechanisms exist, since excised branches may not be able to respond to insect feeding by increasing concentrations of defensive compounds as would a whole branch. However, our study shows that feeding on excised foliage in the laboratory is only a good approximation of feeding as it occurs under natural conditions. Bagging of trees on trees (white muslin bags) tends to increase pupal weights, probably as a result of reduced harassment from predators and parasites possibly because of a modified micro-environment.

Influence of Host Species

A commonly held belief among foresters is that some host species are more resistant to western spruce budworm and eastern spruce budworm,

Choristoneura fumiferana Clemens, than are other hosts. We compared the relative suitability of three of the important hosts in Arizona (Table 3). Pupal weights were not significantly different among the three hosts, which indicates that all hosts are a suitable substrate for insect development. Feeding efficiency (ECI) and growth rate (RGR) were significantly higher on Douglas-fir than on either white fir or corkbark fir. However, budworm larvae can apparently compensate for the lower quality of the foliage, as reflected in low ECI and RGR, by increasing their consumption rate (I) and probably the duration of the feeding period. This ability of insects to compensate for lower food quality by increasing consumption is often overlooked in studies of host plant-herbivore interaction. Too few replicates of Engelmann spruce were available to include in this analysis; however, qualitatively it appeared as if WSBW did quite well on spruce foliage when the host growth and the herbivore requirements were synchronized.

Table 3. Nutritional indices and pupal weights for western spruce budworm reared on three host species in Arizona.

HOST	N	I (mg)	RCR	RGR	ECI	PUPAL WT. <u>a/</u> (mg)
DOUGLAS-FIR	13	185.	1.7	0.12 A <u>b/</u>	7.8 A	58.6
WHITE FIR	20	226.	2.0	0.10 B	5.4 B	60.6
CORKBARK FIR	10	223.	1.7	0.09 B	5.8 B	60.0
F-PROB.		0.341	0.163	0.012	0.003	0.957

a/ pupal weight on fresh basis, all other values based on oven-dry weights.

b/ values followed by different letters are statistically significant, oneway ANOVA, LSD multiple range test, $\alpha = 0.10$.

Chemical Content of WSBW Host Foliage

Current year's foliage of selected host trees was collected seven to 10 days after the beginning of the feeding studies. Foliage was collected from the same trees and crown position as those used in the feeding studies. Tannin concentration did not vary significantly between host vigor categories for any of the species tested (Table 4). Engelmann spruce had approximately twice the tannin content of any other host. Total phenols were not different among vigor categories for Douglas-fir and white fir (Table 5). However, medium vigor corkbark fir trees had lower total phenols than did the high or low vigor trees. Low vigor Engelmann spruce trees had lower total phenols than high and medium vigor trees. Protein content of foliage tended to decrease with host vigor for all host species tested (Table 6). However, this trend was statistically significant only for Engelmann spruce.

Table 4. Percent dry weight of tannins in western spruce budworm host foliage by host vigor class. a/

VIGOR	DOUGLAS FIR	WHITE FIR	CORKBARK FIR	ENGELMANN SPRUCE
HIGH	4.78 A	5.64 A	4.51 A	7.11 A
MEDIUM	3.91 A	4.58 A	4.98 A	9.71 A
LOW	4.98 A	3.79 A	4.40 A	8.86 A
\bar{x}	4.49	4.66	4.63	9.28

a/ values followed by different letters are significantly different, oneway ANOVA, LSD multiple range test, $\alpha = 0.05$.

Table 5. Total phenol content of western spruce budworm host foliage by host vigor class. a/ b/

VIGOR	DOUGLAS FIR	WHITE FIR	CORKBARK FIR	ENGELMANN SPRUCE
HIGH	0.11 A	0.07 A	0.19 A	0.12 A
MEDIUM	0.10 A	0.06 A	0.13 B	0.13 A
LOW	0.09 A	0.06 A	0.18 A	0.08 B
\bar{x}	0.10	0.06	0.17	0.11

a/ total phenols expressed in terms of absorbance per mg.

b/ values followed by different letters are significantly different, oneway ANOVA, LSD multiple range test, $\alpha = 0.05$.

Table 6. Percent dry weight of protein in western spruce budworm host foliage by host vigor class. a/

VIGOR	DOUGLAS FIR	WHITE FIR	CORKBARK FIR	ENGELMANN SPRUCE
HIGH	14.62 A	21.17 A	22.78 A	23.88 A
MEDIUM	12.41 A	20.85 A	19.08 A	22.90 A
LOW	11.69 A	17.47 A	19.86 A	16.77 B
\bar{x}	12.86	19.93	20.57	21.36

a/ values followed by different letters are significantly different, oneway ANOVA, LSD multiple range test, $\alpha = 0.05$.

Relationship Between Foliage Chemistry and Insect Feeding

Pearson's correlation coefficients and a simple linear regression were used to evaluate the relationship between foliage chemistry and WSBW feeding. In each case foliage samples for chemical analysis and feeding were collected from the same aspect and crown position of the same tree. Only Douglas-fir and white fir are discussed here due to insufficient sample size for the other species.

Tannins in Douglas-fir were positively correlated with both foliage ingested and approximate digestibility (Table 7). These results were quite surprising considering that the theory of plant apparency (Feeny 1976, Rhoades and Cates 1976) would predict that the quality of the foliage and subsequent consumption should decrease as tannins increase. Phenols are not significantly correlated with any of the larval growth parameters studied. Protein is positively correlated with pupal weight. Adjusted R^2 values presented in Table 8 indicate that leaf tannin content can be used to predict the amount of Douglas-fir foliage ingested and that protein content is a useful predictor of pupal weight.

Table 7. Correlation coefficients indicating the relationship between Douglas-fir foliage chemistry and western spruce budworm larval growth parameters ($n = 7$).

FOLIAGE CHEMICALS	LARVAL GROWTH PARAMETERS				
	INGESTED	RCR	RGR	AD	ECI
TANNINS	0.72 ^{a/}	0.55	0.62	0.78 ^{b/}	-0.25
PHENOLS	0.26	-0.24	-0.37	-0.46	0.08
PROTEINS	0.64	0.01	0.62	0.41	0.26

a/ $P < 0.10$.

b/ $P < 0.05$.

The relationships between foliage chemicals and larval growth parameters for white fir are different from those observed for Douglas-fir. In this case tannins are negatively correlated with growth rate and efficiency (Table 9). This is consistent with the plant apparency theory. Adjusted R^2 values indicate foliage tannin content can be used to predict growth rate and efficiency (Table 10). Neither phenols nor proteins are correlated with any measure of larval growth for WSBW feeding on white fir foliage.

Table 8. Adjusted R^2 values for simple regression equations using Douglas-fir foliage chemicals to predict western spruce budworm larval growth ($n = 7$). d/

FOLIAGE CHEMICALS (x)	LARVAL GROWTH PARAMETERS (y)					PUPAL WT.
	INGESTED	RCR	RGR	AD	ECI	
TANNINS	0.40 ^{a/}	NS ^{c/}	NS	NS	NS	NS
PHENOLS	NS	NS	NS	NS	NS	NS
PROTEINS	NS	NS	NS	NS	NS	0.57 ^{b/}

$P < 0.10$.

$P < 0.05$.

NS; not significant.

data transformed where appropriate to best fit the form of the relationship.

Table 9. Correlation coefficients indicating the relationship between white fir foliage chemistry and western spruce budworm larval growth parameters ($n = 8$).

FOLIAGE CHEMICALS	LARVAL GROWTH PARAMETERS					PUPAL WT.
	INGESTED	RCR	RGR	AD	ECI	
TANNINS	0.44	0.42	-0.68 ^{a/}	0.45	-0.85 ^{b/}	-0.22
PHENOLS	-0.28	-0.33	-0.38	-0.17	-0.37	-0.27
PROTEINS	0.18	0.14	0.15	0.12	0.13	0.25

$P < 0.10$.

$P < 0.05$.

Table 10. Adjusted R^2 values for simple regression equations using white fir foliage chemicals to predict western spruce budworm larval growth ($n = 8$). d/

FOLIAGE CHEMICALS (x)	LARVAL GROWTH PARAMETERS (y)					PUPAL WT.
	INGESTED	RCR	RGR	AD	ECI	
TANNINS	NS ^{a/}	NS	0.38 ^{b/}	NS	0.64 ^{c/}	NS
PHENOLS	NS	NS	NS	NS	NS	NS
PROTEINS	NS	NS	NS	NS	NS	NS

NS; not significant.

$P < 0.10$.

$P < 0.05$.

data transformed where appropriate to best fit the form of the relationship.

Douglas-fir, corkbark fir, white fir, and probably Engelmann spruce are all suitable host material for WSBW when current foliage flush is synchronized with the larval feeding period. Douglas-fir is of slightly better quality than the other species tested. However, because of the ability of the budworm to compensate for lower food quality by consuming more foliage, larvae can grow and develop quite well on lower foliage quality hosts. It is possible that white fir and corkbark fir could actually sustain more defoliation damage than Douglas-fir because their foliage is of lower quality. This is important to keep in mind when considering low foliage quality as a criterion for selecting resistant species or genotypes. In northern Arizona, Douglas-fir and true firs typically sustain more damage than Engelmann spruce, but this may be primarily because spruce is not phenologically synchronized with the feeding cycle of the WSBW.

There are surprisingly few differences in the tannins and phenols tested among vigor categories. Our study fails to show any evidence that high vigor trees maintain higher levels of defensive chemicals than do low vigor trees. Nor is there any evidence to suggest that by excising foliage, and presumably preventing induction of defensive compounds, insects can perform better than if they feed on a host which could actively defend itself. There may be differences in protein content between vigor categories, but even in the worst case (foliage with only 11% protein) there appears to be adequate protein to sustain insect development.

Differences in tannins, phenols, and proteins among species are more striking. Tannins are almost twice as abundant in Engelmann spruce as in the other species. But, considering the different relationship between tannins in white fir and Douglas-fir and feeding parameters, it is uncertain whether high tannin content has a negative or positive effect. There are differences in phenols between species but, here again, there is no apparent relationship to feeding parameters. Douglas-fir, which based on efficiency and growth rate of larvae is the best host, actually had the lowest average protein content of the host species tested.

Phenols do not appear to influence feeding by WSBW even though the phenolic content in budworm hosts is within the concentration range that has been reported to influence host selection by aphids (Zucker 1982).

The relationship between foliage tannins and some of the larval growth parameters is intriguing. It is likely that the tannins are not identical in Douglas-fir and white fir. But, the levels of tannins are well within the range found by Feeny and Bostock (1968) who argued that higher tannin content is equated with lower food quality. Bernays (1981) suggests that tannins may actually be used as a nutrient source by grasshoppers. In Douglas-fir, tannins were positively correlated with digestibility. In white fir, tannins were negatively correlated with growth and

efficiency. It is difficult to explain these apparently opposite results, except that tannins and proteins are intercorrelated in Douglas-fir which may result in a random correlation. Clearly we know little about the role of foliage tannins in larval feeding and growth in the WSBW.

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PERFORMANCE IN RELATION TO FOLIAR CHEMISTRY

OF ITS HOST PLANTS

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Spruce budworm growth was best on balsam fir, poorest on lowland black spruce, and intermediate on upland white and black spruce. Growth was consistently, positively linked to foliar N and negatively linked to Fe, K, and select terpenes. Survival rates were not strongly, nor consistently linked to any of the measured foliar chemical traits.

The population dynamics of the spruce budworm, *Choristoneura fumiferana*, is clearly an ecosystem/home level process. The process has many parts, all of which interact to some degree, and none of which is really well understood individually, not to mention how they operate together. The process starts, as we see it, by a budworm larva taking a bite out of a plant. The plant has a complex array of nutritive and nonnutritive chemicals that together affect budworm behavior, metabolism and ultimately growth, reproduction and/or death. Our primary objective has been to examine variations in budworm performance among different host tree species in relation to the foliar chemistry of these trees. The ultimate goal is to identify the major host factors regulating budworm performance.

This paper reports on our preliminary analyses of the growth and survival of budworms in relation to total nitrogen, mineral elements, mono-terpenes, and phenolics in its diet on three tree species: balsam fir, *Abies balsamea*; white spruce, *Picea laura*; and black spruce, *Picea mariana*.

This study was conducted in two locations, the main plot being about 20 miles south of International Falls, Minnesota, in Koochiching County, and the secondary plot about 15 miles west of Cloquet, Minnesota, in St. Louis County.

Methods

In 1981, we selected 122 trees for the purpose of monitoring the performance of larval budworms in relation to foliar chemistry of these trees. Among

this set were 20 white spruce, 25 black spruce, and 58 balsam fir which were divided into four classes: 24 small (1-5 m), 16 medium (5-10 m), 8 large (10-15 m), and 10 stress. Nineteen of the medium/large category were selected at random for the purpose of studying both early and late season (i.e., late summer) budworm performance.

On each tree we selected five branches at midcrown level, approximately 70° apart so as to encircle the tree. Each branch was then enclosed with a 36" long fine-mesh cloth sleeve cage which served as an enclosure for 15 second-stage larvae placed therein. Larvae were obtained from the laboratory colony of the Insect Rearing Service of the Forest Pest Management Institute, Environment Canada, Canadian Forestry Service in Sault Ste. Marie, Ontario. Each branch contained at least 30 new shoots. Budworms were removed at the pupal stage and subsequent moths were collected in the laboratory and frozen within 24 hours after emergence in preparation for freeze-drying to constant weight.

We started the experiment in all cases after shoot elongation had begun (approximately 300 degree days, using 2.8°C as the threshold and March 1 as the beginning date). Budworms normally emerge from hibernacula at about 200 degree days in northern Minnesota (Bean and Wilson 1964) whereas in New Brunswick it may be closer to 100 (Cameron et al., 1968). Our records indicate that balsam "bud break" occurred at about 238 DD in our main plot. In 1981, we placed larvae on black spruce about 1 month later (6/22/81) than on balsam and white spruce so as to avoid any possible adverse effects of the late phenology of black spruce. In 1982 all tree species received larvae at 300 DD. Furthermore, in 1981, we also placed second stage larvae on 19 medium/large balsam on July 24. This is about the time that budworm first stage larvae are normally preparing for overwintering.

Foliage chemistry was measured only once during the larval period, at approximately the commencement of the fifth larval stage. This was done because the fifth and sixth stages consume 90-95 percent of the total diet (Miller 1977, Retnakaran 1983). Foliage was gathered from all sides of the tree at midcrown, immediately stored in coolers on dry ice and then frozen at the laboratory until used for analysis. Except for terpene analyses, the foliage was separated from stems, then lyophilized and ground to pass through a 40-mesh screen on a Wiley mill. It was then stored dry in a glass container in the dark until analysis. Details of the various analyses can be obtained from the authors on request.

Because the field studies did not permit control of temperatures during larval development, temperature effects may be confounded with tree effects when comparing budworm performance on different plots and at different times. In all cases we know the daily maximum, minima, and mean temperatures for our experiments as well as the precipitation values. Once we understand the budworm's temperature-growth responses we will be able to remove possible temperature effects from host effects.

Table 1.--Mean adult female and male weights (mg dwt) reared on different hosts in 1981 and 1982

Host plant	1981		1982		1981		1982		n ^{a/}
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
	Females		Females		Males		Males		
BFir stress	21.44	5.64	22.13	5.11	10.24	1.92	12.91	2.95	10
BFir lge	19.28	4.91	22.42	4.32	9.66	2.02	12.40	2.71	8
BFir med	20.42	3.90	20.65	5.74	9.76	1.76	11.99	3.44	16
BFir sml	17.83	3.99	18.78	4.43	9.33	1.69	10.87	2.38	24
WSpr lge	16.81	5.50	18.49	6.33	7.31	1.93	12.43	3.02	10
WSpr sml	15.00	6.05	16.17	6.21	8.20	2.81	9.26	2.93	10
BSpr upld	15.06	10.37	19.04	6.01	8.12	1.89	10.67	2.78	10/20 ^{c/}
BSpr lowld	8.32	3.38	11.10 ^{b/}	3.56	4.92	1.42	6.73	1.79	15
BFir late	13.56	3.09	na	na	7.41	1.78	na	na	18

^{a/} Number of trees in each species class.

^{b/} No data available.

^{c/} Ten trees in 1981, twenty in 1982.

Results

Differences Among Species

Budworms clearly attained the highest adult weights on balsam fir (18-22 mg dwt), followed by white spruce (15-18.5 mg) or upland black spruce (15-19 mg) and then lowland black spruce (8-11 mg) (Table 1). The pattern was consistent between years for both sexes. The fact that white spruce-reared budworms were smaller than those from fir is contrary to results from eastern North America where such spruce-reared budworms are usually about equal to (Blais 1957, Greenbank 1963) or significantly larger (Koller and Leonard 1982, and see T. Thomas in this proceedings) than those from balsam fir. The upland black spruce data agree with previous research which suggests that it produces slightly smaller insects than does balsam fir but not necessarily less than does white spruce (Blais 1957, Greenbank 1963).

Variability in female weights was about 50 percent greater on the spruces than on balsam fir as estimated by the coefficients of variation (SD/ \bar{x}) (Table 1). This was the result of the fact that some spruce trees consistently produced very small insects (< 11 mg) while others consistently produced large insects (> 20 mg) similar to those on large balsam fir.

Generation survival rates (from second instars to the adult stage) in 1981 revealed that balsam fir was a superior host followed by white spruce and then black spruce (Table 2). The pattern changed in 1982, however, showing that white spruce and lowland black spruce were not different from balsam. Upland black spruce, however, again showed the lowest survival rates. We cannot explain differences in the survival patterns between years except to hypothesize that weather conditions may have been responsible. Mean daily temperatures were about 2.4°C higher during the larval period in 1981 than in 1982 (16.7° vs. 14.3°). Mean daily maxima averaged nearly the same (23.8° vs. 22.9°) in both years but daily minima were about 4°C higher in 1981 (9.5° vs. 5.7°).

Table 2.--Survival rates and proportion of females from different hosts in 1981 and 1982

Host plant	Survival rate		Proportion females	
	1981	1982	1981	1982
BFir stress	.290	.282	.48	.5
BFir md/lge	.305	.276	.55	.4
BFir sml	.330	.327	.54	.5
WSpr all	.232	.351	.53	.5
BSpr upld	.130	.179	.71 ^{a/}	.4
BSpr lowld	.120	.275	.60*	.5
BFir late	.157	na	.53	n

^{a/} Significantly ($p \leq .05$) different from .50 ratio

Differences Among Age Classes

We studied budworm performance on three age/size classes of trees (3-5 m, 5-10 m, 10-15 m) known as small(s), medium(m), and large(l), respectively. All trees were nearly open grown most had full tree crowns. Large trees were bearing male flowers in the upper half crown level whereas only few of the medium and none of the small trees were flowering.

In both balsam and white spruce, there was a consistent trend for small trees to produce the smallest insects. This pattern held between years and for both sexes. For example, the female mean dry weights (mg) for each size class shown in the following tabulation are significantly different ($p \leq .05$) from one another:

1981	BFir: 20.35(m) 19.26(l) 17.83(s)
1982	BFir: 22.42(l) 20.65(m) 18.78(s)
1981	WSpruce: 16.81(l) 15.09(s)
1982	WSpruce: 18.49(l) 16.17(s)

The smallest difference between mean female weights on small and the large-medium classes ranged from 1.4 to 1.9 mg on balsam and 1.7 to 2.3 mg on white spruce. The differences imply that insects growing on large-medium trees averaged at least 10 percent larger than those from small trees and in some cases as much as 20 percent. Survival rates, however, did not vary significantly among age classes (Table 2). Therefore, although small balsam and white spruce produced smaller insects, they did not produce lower survival rates than larger trees. In general, for both balsam and white spruce, mean insect weight gains and survival rates per tree had no correlation with one another.

Differences Owing to Phenology

On July 24, 1981, we "planted" second stage budworm larvae on 19 medium-large balsams. This date is nearly 2.5 months later than budworm second stage larvae normally emerge for feeding in northern Minnesota. The larvae on these trees attained only about two-thirds the size (13.56 mg) of normal early-season larvae (Table 1). Furthermore, survival was only about half (16%) of that experienced by the similar early-season cohort (Table 2). This was not unexpected because late summer foliage conditions are drastically different from those of early season. The fact that budworms performed as well as they did, however, was surprising. Mean daily temperatures during this late season experiment were about 2°C higher (18.9° vs. 16.7°) than during the early season experiments.

Differences Owing to Stress Treatments

Ten trees (7 medium and 3 large) were trenched at a radius of 10 feet from the trunk in the spring of 1980 down to depth of about 30 inches. This depth reached well into the mineral soil layer or hit bedrock since the study plot was on top of a rock outcrop covered with shallow soils. The ground area under each tree canopy was then covered with black polyethylene plastic. Trees were monitored for moisture stress by pressure bombing twigs that were collected near the bottom of the crown. Pressure bomb readings were taken once per week and two times per day (before 8:00 a.m. and after 2:00 p.m.), during the 6-week larval growth period. The following tabulation shows the mean seasonal pressure bomb differences (stress-control) at both a.m. and p.m. samples:

	<u>a.m. difference</u>	<u>p.m. difference</u>
1981	0.50 bars	0.89
1982	0.45 bars	0.78

Mean differences in water potential between stress and control trees were usually less than one bar--suggesting that the stress treatment was relatively weak. The differences were nevertheless statistically significant on half of the sample periods each summer.

Stress trees produced significantly larger female and male insects than the control trees (all medium and large firs combined) (Table 1). However, in 1982 only males were significantly larger than

those from the control trees. The mean weight differences (stress-control) for each sex are shown in the following tabulation:

	<u>Females</u>	<u>Males</u>
1981 (Stress-Control):	1.31 mg	0.53
1982 (Stress-Control):	0.79 mg	0.80

Thus, so far, the induced stress treatment has had only a minor enhancing effect on budworm growth. However, it has not had any effect on survival rates (Table 2).

Budworm Performance in Relation to Foliar Nutrients

Theoretically an insect's performance should vary in relation to its dietary needs and a diet's deviations from these needs. In the case of the spruce budworm, no one really yet knows what the particular details of its needs are. Mattson and Koller (1981) proposed that the minimally optimal foliar N value for female performance is about 2.1 percent dwt. Harvey (1974) proposed that the minimally optimal levels of soluble sugars in the female's diet is about 4 percent fwt or 20 percent dwt. Albert *et al.*, (1982) found that peak behavioral (i.e., feeding) response to soluble sugars (sucrose) in the diet occurs at about .03M or less than 1 percent fwt. Thus diets deviating negatively from these values probably will produce smaller insects and/or longer growth and feeding periods. Requirements for other important dietary components are really unknown.

To obtain a perspective on the budworm's needs for the mineral elements, we analyzed the nutrient levels in the bodies of adult males and females collected from the trees in our study and then compared their body levels to their food levels (Table 3). The data reveal that the elemental concentrations showing highest deviations from foliar levels are as follows for males and females:

Females: Na>N>P>Cu>Zn>Fe>Mg>K>Ca>Mn
Males: Na>N>Cu>P>Zn>Fe>Mg>K>Ca>Mn

Sodium clearly had the highest magnification factor (MF) (60.9 and 13.4), but owing to possible errors in its measurement on our emission spectrometer we consider the results very tentative. Nitrogen, P, and Cu were clearly the next highest, with all elements down to Fe showing MF's greater than two. All the rest were smaller than one. MF is concentration in insect body divided by concentration in foliage. Studying the budworm's utilization efficiencies of mineral elements in a low-salt McMorran (1965) meridic diet gave nearly the same results as the above magnification factor array:

Cu>N>Zn>P>K>Mg>Fe>Ca>Mn

The utilization efficiencies array is somewhat different from MF array because the artificial diet does not exactly match the levels of elements contained in the foliage. The point is, though, that any variations in budworm performance on different hosts will most likely be due to variations in the limiting nutrients--those having highest magnification factors or utilization ratios.

Table 3.--Concentrations (ppm dwt) of mineral elements in the bodies of male and female spruce budworm adults, and balsam fir foliage (6/22/82), and the ratios of insect/foliage elemental concentrations

Item	%N	P	K	Mg	Ca	Zn	Fe	Na	Cu	Mn
SBW Female										
Mean	7.97	7,539	9,932	861	290	113	73	56	12	4
SD	.44	308	800	101	97	22	43	21	4	3
SBW Male										
Mean	9.51	9,569	10,855	987	340	117	87	128	19	6
SD	.40	642	892	83	73	23	51	38	8	4
Fir foliage										
Mean	1.26	1,872	12,738	927	3,671	34	31	9	4	303
SD	.10	108	1,704	109	646	4	4	2	1	103
♀ SBW/foliage	6.3	4.0	.78	.92	.08	3.3	2.4	6.1	3.3	.01
♂ SBW/foliage	7.5	5.1	.85	1.06	.09	3.4	2.8	13.9	5.4	.02

Growth in Relation to N and Mineral Elements

Balsam fir. Regressing male and female dry weights against the foliar elemental concentrations they experienced as fifth and sixth stage larvae revealed that nitrogen was the only variable consistently and positively related to growth (Table 4). Calcium had a significant positive effect on female weights in 1981 but this is probably spurious owing to the fact that the larvae need only about 300 ppm calcium or less in their diets and foliage has about 15-fold this level. Calcium, of course, could be related to some other important foliar variable which in turn affects larval growth. For example, it was negatively correlated ($p < .05$) with both tannins and phenolics. Calcium may form chelates with many kinds of phenolics, perhaps rendering them less deleterious to a leaf consumer. The effects of the other elements (K, Fe, Cu) were, to our surprise, all negative. For example, based on the body/foliage magnification factors, we expected that Fe and Cu were in relative short supply, but their negative correlation with weight gain implies otherwise. However, as in the case of calcium, their correlation need not imply direct cause and effect but some indirect effect. K, for example, was significantly positively correlated with 10 mono- and sesqui-terpene species in balsam fir and with the terpene grand sums. Fe, on the other hand, was negatively correlated with four terpenes and Cu positively with three. In general, all foliar elements tended to show a negative correlation with total phenols and condensed tannins.

Late season results were unlike the early season results in that K and Cu were now positively correlated with weight gain (Table 4). For both elements, however, late season levels were less on the average than they were in early season (e.g., K: 8000 vs. 10,482). Not only were they less, they were much more variable (e.g., CV-K = .22 vs. CV-K = .08). Late season Cu levels were probably below optimal, for more than half of the late

season trees had less than 0.5 ppm in their foliage. Early season trees, on the other hand, averaged about 4 ppm--none going below 2.6 ppm. When Cu occurred at similar levels (4 ppm) in the meridic diet, budworms more completely (ca. 60-75 percent) extracted it than other elements that occurred at levels comparable to early season foliage. N was not a significant late season nutrient variable for both sexes but only for males, probably owing to its relatively uniform concentration among late season trees (CV-N = .08 vs. CV-N = .14).

Table 4.--Significant variables in the regression of mean male and female adult dry weight per tree on foliar mineral element concentrations in different host trees and years

Host species	Significant Variables				R ²	a/n
<hr/>						
Females						
BFir-79	+N	-Fe			.69	12
BFir-81	+N	-Fe	-K	+Ca	.44	50
BFir-late	+K				.17	18
Males						
BFir-79	+N	-Cu			.47	12
BFir-81	+N	-Fe	-K		.18	50
BFir-late	+N	-Fe	+Cu		.33	18
Females						
WSpr-81	+N	-K	-Zn		.61	18
BSpr-81	+N	-K			.66	17
Males						
WSpr-81					.00	18
BSpr-81	+N	-Mn	-Cu		.76	17

a/ Number of trees in the regression.

Spruces. As with the firs, N was the only element showing a consistent, positive relation to eight gain for both sexes (Table 4). All other elements were negative; thereby corroborating the pattern seen for early season balsam fir. The consistently negative contribution of K stands out because K levels in black spruce were even lower in most cases than they were for late season balsam (5000 ppm vs. 8000 ppm). Thus one is obliged to conclude that K itself is not directly affecting eight gains but indirectly through its effect on some other plant traits. For example, plant K was positively associated with every terpene species but one in both black and white spruce. We hasten to add that none of the associations was statistically significant though. This is probably at least partially due to a small data set which will be enlarged in the next few months. As before, the negative contribution of Cu is difficult to explain because copper was close to its minimally optimal level in the foliage diet. On the other hand, manganese may be approaching deleterious levels in the foliage because it's about one-hundred fold more abundant there than in the insect's body. Moreover, excessively high levels of one mineral element can interfere with the absorption and utilization of other elements and nutrients (Maynard *et al.* 1979). No explanation is readily available for zinc's negative contribution because its level in the foliage (46 ppm) is hardly excessive. In fact, at this level in the artificial diet it is highly utilized and supports good growth.

Survival in Relation to N and Mineral Elements

Regressing generation survival (the arcsin transformation of the survival rate) against foliar elements revealed that none accounted for more than 10 percent of the observed variation and in most cases, they accounted for only about one-third of the variation (Table 5). Moreover, there was no consistency between years or between species. Therefore, we feel that the observed results may be entirely an artifact.

We were also surprised to learn that insect eight gains (FWT, MWT) and survival rates per tree were not significantly correlated with one another except on black spruce (*) where the relationship was negative ($p \leq .05$) contrary to expectation:

	BFir	WSpr	BSpr	Late BFir
MWT	.11	.13	-.51*	.23
FWT	-.03	-.28	-.56*	.16

The latter result may suggest that foliage was in short supply and hence higher survival meant less food per insect and thus lower growth. On the other hand, it also could suggest that the tree traits governing survival and growth of budworm are linked in opposing directions, or perhaps not at all in the case of fir and white spruce.

Table 5.--Significant variables in the regression of generation survival rates per tree (2d→adult) on foliar mineral elements and phenolics (PH) in different host trees and years

Host species	Significant variables	R ²	a/ n
BFir-79	+Fe -PH	.32	39
BFir-81	+Mn +Cu	.31	50
BFir-late	+N	.18	18
WSpr-81	+Cu -K -Fe +PH	.52	18
BSpr-81	+Mg	.33	18

a/ Number of trees in regression

Budworm Performance in Relation to Allelochemicals

Terpenes

Preliminary analyses reveal that several terpenes are significantly negatively correlated with weight gain for both sexes in both balsam fir and white spruce. In the case of balsam fir, the following six species of monoterpenes were negatively correlated ($p \leq .05$) with growth except where noted (ns):

	alpha-pinene	beta-pinene	camphene	beta-phellandrene
MWT	-.36	-.37	-.43	-.38
FWT	-.32	-.32	-.40	-.25

	bornyl acetate	terpinolene	terpene grd sum
MWT	-.24	-.30	-.62
FWT	-.16 ns	-.24	-.45

None of the terpenes in balsam fir, in fact, were significantly positively correlated with growth.

In the case of the white spruce, five different compounds were significantly negatively correlated ($p \leq .05$) with growth except where noted (ns) as shown in the following tabulation:

	camphor	Sesquiterpenes & monoterpene			alcohols
		#1	#2	#14	#35
MWT	-.33 ns	-.69	-.19 ns	-.32 ns	-.57 ns
FWT	-.71	-.64	-.66	-.68	-.65

Only one terpene showed a positive relation to growth. The fact that white spruce and balsam may have different terpenes regulating budworm performance is not extraordinary because the two trees have different kinds as well as amounts of the individual terpenes. For example, balsam at mid-June had a terpene grand sum of about 6,700 ppm fwt vs. 836 ppm for white spruce. In other words, balsam has roughly 8-fold more terpenes. Black spruce was similarly terpene-rich having about 6,200 ppm fwt in mid-June. This suggests that if it's the total amount of terpenes that are

deterrent, then budworm performance should be better on white spruce than on either balsam fir or black spruce, all other things being equal. The data, however, show the contrary. What is the explanation? Particular species-unique terpene compounds may be especially deterrent at low levels in white spruce (e.g., camphor). On the other hand, all other things are not equal. For example, lower plant nitrogen levels may make white spruce significantly less suitable than fir in spite of its lower terpene levels. White spruce, for example, had 20 percent less N in mid-June than did balsam fir (e.g., 1981: 1.24 percent vs. 1.52 percent). We know that this is due to the fact that white spruce grows faster than balsam fir and thereby dilutes its foliar nutrient levels similarly faster (Fig. 1).

Going back to the hypothesis of the effects of terpene grand sums on budworm growth leads us to differences between small and medium/large balsam. As we said earlier, small trees produced 10 to 20 percent smaller insects than did medium/large trees. This may have been due to the fact that small trees had 42 percent more terpenes than did medium/large trees at mid-June when larvae were in the 5th/6th instars (9,547 ppm fwt vs. 6,700 ppm). The N levels in these two age classes were nearly identical (e.g., 1981: 1.50 vs. 1.55), so this is not a large potential source of variation. We also know that mineral element differences are not a likely explanation of the difference because they appeared to be available in sufficient amounts in both age classes, barring any negative interactions with tannins and phenolics. Similarly, there were

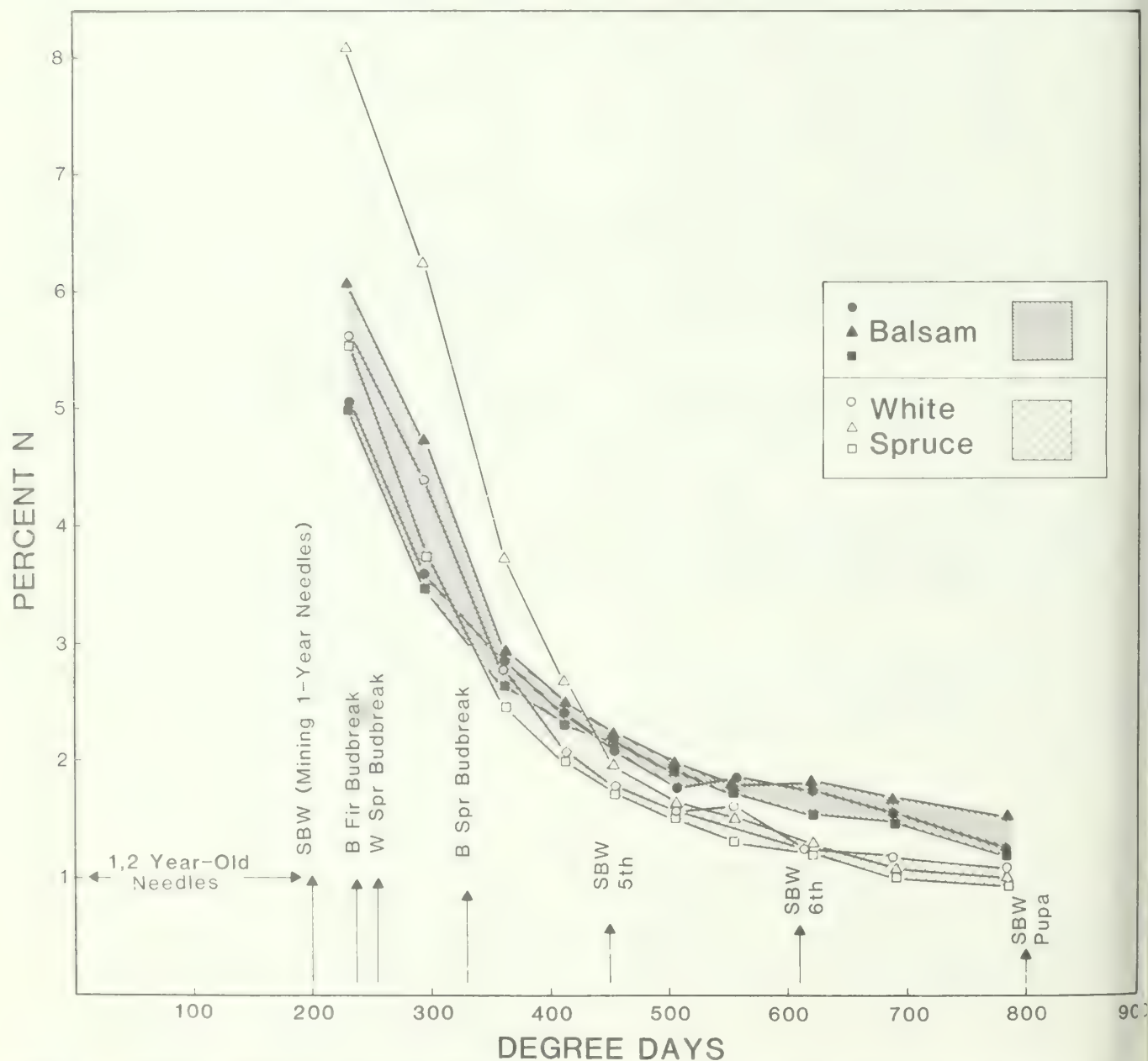


Figure 1.--Seasonal change in foliar nitrogen content (percent dwt) of three balsam and three white spruce with respect to degree day accumulations (2.8°C as base), and the phenology of the spruce budworm.

no significant differences between the two groups for total phenols (2.64 percent vs. 2.59) or tannins (3.8 vs. 4.5 percent). Therefore, until the final analyses are complete, we suggest that the budworm growth difference between balsam age classes is due in large part to their terpene differences.

Small white spruce also had smaller insects and more total terpenes than did large white spruce (994 ppm fwt vs. 667 ppm). But, in this case, male and female weights were not correlated with terpene grand sums. The most likely explanation for differences in insect weight gain between white spruce age classes is the difference in levels of the one or more of individual terpene compounds listed above. There were no significant differences in tannins, total phenolics, and N levels between the two age classes just as was the case for balsam.

Phenolics-tannins

Incorporating phenolic and tannin estimates along with the mineral element data in the multiple regressions did not change any earlier conclusions for balsam fir but did in the case of male weight gain on white spruce. In this case, tannin was the only variable significantly correlated with male weight ($r = -.46$). This reflects the fact that no other variables were previously related to male weight gains.

The simple correlation coefficients between phenolics, tannins and weight gains on fir and spruce were not significant in all but two cases *) as shown below:

	Balsam		White Spruce	
	FWT	MWT	FWT	MWT
phenolics	-.29*	.00	.19	.02
tannins	-.06	.13	-.20	-.46*

In general, levels of tannins and phenolics were negatively correlated with nearly all mineral elements in fir and white spruce. In the case of spruce, however, only one of the correlations was significant. This is in striking contrast to balsam where only five out of eighteen negative correlations were not significant in both 1979 and 1981, 2 years for which we have substantial data sets. The following tabulation shows the significant ($p < .05$) tannin and phenolic correlations with N in balsam fir foliage:

	N-79	N-81
phenolics	-.62	-.45
tannins	na	-.42

Palmer (1982) found the same negative relationship between phenolics and N in Populus tremuloides foliage.

Previous studies on the effects of phenolics and tannins on the growth performance (via lowered protein utilization) of folivorous insects have almost unanimously come to the same general conclusion: there seems to be little or no measurable deleterious effect, except perhaps at extraordinarily high tannin concentrations (Lawson et al. 1982, Bernays 1981, Fox and McCauley 1977).

While our analyses are too preliminary to come to any firm conclusions, we believe that there may also be long-term, subtle effects that have been overlooked in the typical growth bioassays which usually measure insect performance (nutritionally and behaviorally) for only one or two instars, or at most for the whole feeding period of one generation. Tannins and/or phenols could have some chronic, subtle effects, such as through the chelation of micro-nutrients like Cu, Zn, and Fe--which then renders them less available to the insects. Such effects would have to be monitored over two or more successive generations to see the impacts of chronic micronutrient deficiencies. The chelation of such micronutrients may also be an important plant defense against microorganisms and could also thereby affect essential gut microbes or pathogens in those consumers having such microsymbionts (Swinburne 1981, Radhakrishnan and Sivaprasod 1980, Roy and Mukherjee 1979, Shieh et al. 1968, Emery 1982).

Budworm Growth Response to N Levels

The analyses have indicated that budworm weight gains are consistently but not exclusively linked to variations in plant foliar N levels. In those cases where N was not implicated, there was usually only very little variation in N levels among plants. Therefore, to add strength to the N hypothesis, we planned two experiments to raise the level of nitrogen offered to larvae, thereby hoping to elicit increased growth. The first experiment was designed to raise dietary N for just the first three instars (2, 3, and 4), whereas the second was designed to raise N for the whole larval life span, but particularly for late stage (5, 6) larvae.

Diet/Foliage Transfer Experiment

In the early spring before budbreak occurs, second stage budworm larvae mine 1-year-old or sometimes 2-year-old needles for 1 to 2 weeks (Blais 1979, McGugan 1954). After molting to the third instar, larvae then move to the newly opening buds or male flowers for feeding. During the needle mining period budworm subsist on very little N, such needles, usually having between 0.95 and 1.1 percent N. The newly flushed foliage, on the other hand, is very N rich (as high as 8 percent) but very ephemeral because shoots and needles are rapidly expanding thereby causing a precipitous decline in most foliar elements (Fig. 1), probably owing to a dilution effect. The decline takes the form of a negative exponential ($\%N = aX^{-b}$) as has also been reported by Shaw and Little (1977). By the fifth larval stage N levels are ≤ 1.5 percent in balsam, and somewhat less in white spruce owing to its faster development and nutrient dilution (Fig. 1). Since the fifth and sixth larval stages eat about 95 percent of the whole food budget for the larval period, (Retnakaran 1983, Miller 1977) we asked whether a consistently high N diet for the first three feeding stages (2, 3, 4) would have any enhancing effect on ultimate weight gain if these larvae were then transferred at the 5th instar to a low N foliage diet. To test this hypothesis we simultaneously grew insects on meridic diet (McMorran 1965) having about 4.4 percent N and also on the natural hosts, balsam and white spruce. At the fifth larval stage, ten females were

transferred from the diet to each of 48 balsam fir and 20 white spruce trees for completion of feeding. At pupation all insects were removed and later weighed for adult body size. The results on balsam showed that diet/foliage reared larvae were significantly larger (9 percent) than foliage/foliage reared insects (20.51 vs. 18.87 mg). Furthermore, plotting mean female weights of each group from a tree against the foliar N values they experienced as fifth and sixth stage larvae gave nearly identical regressions except for the intercepts which reflect their mean differences in body size:

diet/foliage FWT = $12.06 + 5.42\%N$ $r^2 = .19$
 foliage/foliage FWT = $10.37 + 5.46\%N$ $r^2 = .22$

Thus the early diet ration seems to have "bumped up" final adult weights.

On the other hand, the same experiment on white spruce gave opposite results; diet/foliage insects were about 9 percent smaller (14.18 vs. 15.50 mg where $.1 < p < .05$). There was no significant regression of either group on foliar N values but the two groups nevertheless performed similarly on the set of 20 spruce as evidenced by the significant regression between their respective mean adult weights:

$FWT (d/f) = 6.72 + .481 FWT (f/f)$ $r^2 = .30$

These results are in direct contrast with those reported by Thomas (this proceedings) who found that diet to current white spruce foliage transfers (at the 6th larval stage) produced larger insects (ca. 21 mg) than similar transfers to balsam fir (ca. 15 mg). The explanation for this divergence from our results could be due to several factors: different populations of insects, different physical environments, and different host materials. The latter one entails at least two variables. Thomas used excised branches of both fir and spruce whereas we used intact branches. Perhaps even more important is the fact that the eastern populations of white spruce and fir are known to differ (phytochemically) from the more western populations such as the one we studied in northern Minnesota (Wilkinson *et al.* 1971, von Rudloff 1975, Zavarin and Snajbeck 1972, and Lester 1974). For example, von Rudloff (1975) reported that camphor levels are nearly twice as high in some western populations of white spruce than in eastern ones. However, until more is also known about the nutrient levels of the eastern host materials, it's impossible to explain the causes of the apparent differences in budworm performance.

To recapitulate, the balsam fir transfer experiment suggested that giving young larvae a high protein diet enhanced their performance by an amount that was constant, when the N effect on late larvae was accounted for. On the other hand, the spruce transfer experiment suggested that the early high protein diet was not enhancing, for these larvae attained smaller size than those having spent their early instars on spruce. Nevertheless both diet and tree insect groups performed similarly with respect to the trees they were on. The following tabulation summarizes the transfer effects on adult female dry weights relative to the

meridic diet control:

	diet/wsp	wsp/wsp	bfir/bfir
Mean female weight (mg)	14.18	15.50	18.87
	diet/bfir	diet/diet	
Mean female weight (mg)	20.51	26-31	

Obviously, feeding for the fifth and sixth larval stage on a tree was not as good as feeding on the diet. White spruce insects achieved about half, and balsam insects about two-thirds of their potential size. Why the meridic diet experience enhanced growth on fir but disenanced it on spruce is an enigma. Perhaps early season spruce foliage is superior to the artificial diet. On the other hand, later in the season, it is plainly inferior. One can speculate that there must have been significant transfer shock going from diet to trees, especially in the case of white spruce. Perhaps the shock was due to higher metabolic cost to operate the budworm's mixed-function oxidase system on spruce than on fir (Brattsdén 1983). This assumes, of course, that there were allelochemicals that elicited higher MFO activity on spruce than on fir or that there were present significant MFO inhibitors in the spruce foliage which may have rendered spruce allelochemicals more deleterious. On the other hand, the effect may have occurred at the behavioral level, for spruce foliage seems to harden off faster than balsam, and it might also possess important feeding deterrent (e.g., pungenin) (Heron 1965).

Fertilization Study

To elucidate the budworm growth response (ΔW) to changes in foliar N (ΔN), we first regressed budworm weight gains in 1981 on foliar N levels. Secondly, we fertilized our most N-impooverished trees, the lowland black spruce (3-5 m tall and 30-45 years old) and half of the small balsam which are comparable to trees used in two earlier fertilization studies (Shaw *et al.* 1978, Shaw and Little 1972). In each case we had 15 treated and 15 control trees. We applied 600 lbs. N/acre (urea) around the root zone of each tree during the first week of May 1982.

Male and female weight gains (MWT, FWT) in 19 were clearly linear functions of foliar N (using all tree species and age classes):

$FWT = 3.45 + 9.844 (\%N)$ $r^2 = .54$ $n = 114$
 $MWT = 3.13 + 3.959 (\%N)$ $r^2 = .44$ $n = 113$.

Scatter plots of the data revealed that female weight gains showed a clear positive trend over the full range of N values (0.47-2.05%). Furthermore, female weights increased with even higher N levels (2-4%) administered in the form of casein and wheatgerm in artificial diets. Male weights, on the other hand, showed little tendency to increase with foliar N levels above 1.5%. Moreover, administering even higher levels of N (2-4%) in artificial diet brought about a weak response, 1-2 mg, suggesting that above 1.5% N males have a shallow response potential if any.

The linear regressions imply that the weight response of budworms to an increment of N is constant, e.g., $\Delta FWT/\Delta N = 9.84$, the slope of the regression line. In other words, for each unit increase in foliar N there is a concomitant 9.8 mg increase in female weight. In the case of the fertilization study, our treatment of 600 lbs. urea elevated foliar N levels by 0.40 and 0.45% in the black spruce and balsam fir trees, respectively. These N changes both elicited 1.38 mg increases in female mean weights as shown in the following tabulation:

	FWT	ΔFWT	MWT	ΔMWT	%N	$\Delta \%N$
Black Spruce	18.78	1.38	10.87	0.37	1.31	0.45
Balsam Fir	20.16		11.24		1.76	
Black Spruce	11.10	1.38	6.73	0.96	0.85	0.40
Balsam Fir	12.48		7.69		1.25	

Urea treatment caused significant ($p < .05$) increases in female weights on both tree species. Significant increases in male weights only on black spruce. The fact that the males did not respond to urea fertilization on balsam lends support to our suspicion that males have a low minimal dietary N requirement (perhaps about 1.5%) and that near this level their response is nearly constant.

Using the fertilization data for females only, we calculate that $\Delta FWT/\Delta N$ for balsam and black spruce are 3.07 and 3.45, respectively. These values are not much different from those derived from the fertilization experiments of Shaw *et al.* (1978). They reported that high and low urea treatments raised foliar N values (on June 23) by 0.40 and 0.4%, respectively. These increments in N elicited female adult dry weight gains (using formula of Mattson *et al.* 1982) of 3.33 and 3.3 mg. Thus $\Delta FWT/\Delta N$ was 4.16 and 2.83 for the high and low urea treatments, respectively. Shaw *et al.*'s high calcium nitrate treatment gave a $\Delta FWT/\Delta N$ value of 2.86. Therefore, pooling Shaw *et al.*'s and our values suggests that $\Delta FWT/\Delta N$ averages about 3.27 and ranges from 2.83-4.16. In other words, $FWT = a + 3.27 (\%N)$. This implies that for every 1% increment in foliar N, there will be a corresponding 3.27 mg dwt increment in adult female weights.

On the other hand, our earlier regression analysis suggested that $\Delta FWT/\Delta N$ should be about 9 instead of 3. What's the explanation for this discrepancy? The explanation might lie in the fact that changing foliar N through fertilization results in many other changes in foliar chemistry that are not all enhancing. For example, fertilization is also known to raise the levels of monoterpenes and sesqui-terpenes. Moreover, the fertilization studies reported herein (Shaw *et al.* 1978) were done on young balsam fir which we have already shown to have significantly higher terpene levels than older trees. Thus the budworm responses (ΔFWT) on small trees might be significantly less than on older trees which have higher levels of terpenes. Similarly, the lowland black spruce which we fertilized probably has

levels of terpenes at least as high and total phenolics levels that are higher than the small fir. Thus the overall 1981 regression may have a higher slope or predicted weight increment per unit of N because the pooled data consists of such species as white spruce and medium/large balsam which may have higher levels of N relative to terpenes, thereby giving higher weight gains per unit N increment than would small balsams and lowland black spruce.

Changes in Fecundity

In order to obtain some idea of the potential impact of different dietary regimes on budworm population dynamics, we used the fecundity/pupal size equation of Miller (1963) and the adult dry weight/pupal size equation of Mattson *et al.* (1982) to project changes in female dry weight into changes in egg output. The resulting formula for fecundity in relation to body size is as follows:

$$F = -442.1 + 216.7 (FWT)^{.37}$$

$$\Delta F = 81.04 (FWT)^{-.63} \Delta FWT$$

The second equation says that changes in egg output (ΔF) increase directly with changes in body size (ΔFWT). In other words, a 2 mg change in body size elicits exactly twice the output of a 1 mg change and so on, holding initial body size (FWT) constant.

The question yet to be answered is how large are the differences in fecundity between insects having different sizes. For example, female budworms from small balsam averaged 32 less eggs than similar females on medium balsam (187 vs. 219) (Table 6). Similarly insects from small white spruce averaged 26 less eggs than females from large white spruce (148 vs. 174). In the case of black spruce, females from the lowland trees averaged 117 fewer eggs than those from upland trees (32 vs. 149).

In the case of the fertilization experiments, we estimated that increasing foliar nitrogen levels by 1.0% would result in roughly a 3 mg increment in female weight. This translates into 41 more eggs for females that weighed 17 mg before fertilization. If foliar N increased only 0.5%, the result would be about half as many eggs, i.e., 20 more per female.

The significance such differences in egg output have on the insect's population dynamics cannot, of course, be answered. These are questions that must be addressed through an ecosystem level model which incorporates all of the major factors regulating budworm natality and mortality.

CONCLUSIONS

Although the study is not yet completed, there are some consistencies that seem substantial enough to warrant recapitulation.

There are clear differences in budworm growth between small and large tree classes, larger trees producing larger and hence more fecund insects. Furthermore, there are differences between species--balsam giving rise to larger insects than white spruce. This pattern seems not to hold in eastern North America where the reverse is true. The explanation for this inconsistency may reside in the fact that the phytochemistry of the eastern and western tree populations are different owing to limited gene exchange, different geological histories, and different environments. There is also, of course, the possibility that the insect populations are substantially different as well.

Budworm survival rates did not vary among tree size/age classes and appeared to be highest on balsam and lowest on black spruce. Survival rates and budworm weight gain per tree were not correlated except in the case of black spruce where the association was negative. This implies that the plant traits which affect weight gain are independent of those that affect survival except perhaps in black spruce where they could be negatively linked. Budworm survival rates were not consistently linked to any variables that were measured.

Insect weight gains per tree were consistently, positively linked to foliar N and negatively to Fe and/or K. The negative associations with Fe and K are surprising because neither element occurs at levels high enough to be minimally optimal much less toxic or noxious. Nevertheless, iron levels in the insect body show a tendency to decrease with increasing levels in the diet. Iron, in fact, is the only element showing this inverse behavior. Moreover, iron concentrations in the insect are also negatively correlated with insect size. What this implies is not clear. It may mean that insects sequester less Fe per unit body weight when diets are better for growth. Fe concentration is also positively correlated with $(1/N)$ of the diet. Since total consumption is usually positively linked to $(1/N)$, Fe uptake by the insect may be related to the total amount of Fe passing through the digestive system.

Potassium levels by themselves may not be inhibitory to budworm growth but K is linked positively to foliar terpene levels which apparently are inhibitory.

Terpene levels were negatively linked to budworm weight gains both on balsam and on white spruce. In the case of balsam, terpene grand sums (all molecular species pooled) showed the strongest correlations whereas in white spruce individual compounds not the grand sums had the highest linkage to weight gain. Difference in budworm performance between tree age classes may be largely due to higher levels of terpenes in the younger trees. Because plant terpene profiles are known to exhibit significant east-west variation across North America, it is likely that budworm performance on these trees will similarly vary.

The significance of phenolics and tannins in the performance of spruce budworm is still uncertain. The early data suggest little effect on either survival or weight gain. However, the

spectrum of phenolic compounds in balsam and the two spruces has not yet been examined so it is entirely possible that one or more of them could have significant behavioral or physiological effects. Pungenin, for example, in white spruce could be an important feeding deterrent.

Finally, it is clear that changing insect N intake through artificial diet to foliage transfer and fertilization results in enhanced insect growth, at least on balsam fir. The data suggest that growth increment per unit nitrogen increment ($\Delta FWT/\Delta N$) is about 3, as long as the minimally optimal level of N in the diet has not yet been reached. We suspect that the growth increment per unit nitrogen increment ($\Delta FWT/\Delta N$) will vary with different host species and age classes owing to different background levels of nutrients and allelochemicals.

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MOTH IN THE NORTHERN DECIDUOUS FOREST

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ABSTRACT

Both gypsy moth host preferences and the foliage characteristics that have been implicated as factors in host selection were monitored from 1979 to 1982 in a *Quercus-Acer-Ostrya* forest near Montréal, Québec. The preliminary analyses of these data suggest the hypothesis that gypsy moth larvae preferentially attack trees that have high sugar:tannin ratios in their young foliage.

The gypsy moth, *Lymantria dispar* L., is recognized as unusually polyphagous both in its native Eurasian habitats and also in eastern North America where it is introduced. Of the approximately 185 trees native to Europe (Polunin and Everard 1976) gypsy moth larvae have been reported to feed on the foliage of 75 (Kurir 1952; Györfi 1960). Similarly in the forests of northeastern North America where the gypsy moth has become established, the larvae can feed on at least 86 (Mosher 1915; Forbush and Fernald 1896) of the approximately 169 available native trees (Little 1979). Such a high degree of polyphagy among tree-feeding macrolepidopterans is matched by only a very few species (Fig. 1). This potential breadth of diet combined with the fact that not all trees are equally preferred as hosts (Lechowicz and Jobin 1983) makes the gypsy moth especially useful in developing and testing hypotheses about the interactions between woody plants and the herbivores that feed on their leaves. The gypsy moth essentially provides a bioassay to call attention to traits that make trees better or worse hosts to defoliating insects. If we can understand the basis for gypsy moth host selection, we may hope to gain some general insights into the forest defoliator-host interaction, particularly into the causes and potential control of insect outbreaks leading to catastrophic defoliation.

Two general types of explanation have been put forward as mechanisms underlying host selection by lepidopteran larvae. These may be distinguished as behavioral versus ecological explanations. Behavioral explanations focus attention on proximate cues involving repellent and attractant compounds that influence larval feeding behavior; this approach most often draws

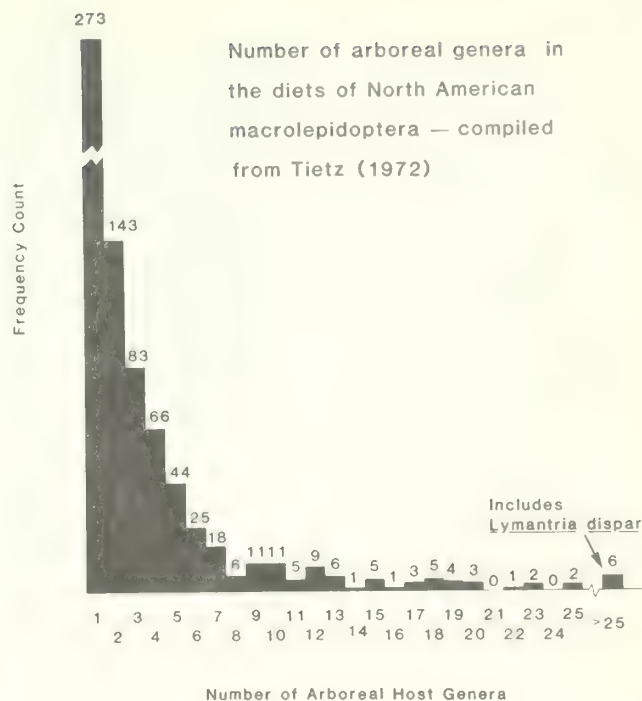


Figure 1. Numbers of genera of trees acceptable in the diets of North American macrolepidopterans; compiled from Tietz (1972).

on evidence from laboratory feeding trials and neurophysiological monitoring of sensilla exposed to test compounds. Dethier (1982) provides an interesting historical review of this literature. Ecological explanations focus attention on the nutritional quality of potential host foliage and assume that natural selection has led to preferences for hosts with relatively nutrient-rich foliage low in toxic or digestibility-reducing compounds. Although such ecological explanations have a long history (see Futuyma 1983 for a recent review) they received increased attention after Feeny (1976) and Rhoades and Cates (1976) independently proposed a general theory of plant defense against herbivores. These two types of explanation are not mutually exclusive; evolution should generally lead to proximate behavioral cues which result in larvae feeding on hosts of high nutritional quality.

In the work described in this paper I have taken an ecological rather than behavioral approach to attempt to understand the basis of larval host preferences in the gypsy moth. Working in a forest southeast of Montréal, Québec, which is near the northern limit of both the deciduous forest and the gypsy moth in North America, I initiated a long term study of gypsy moth host selection and of various tree characteristics which have been suggested to influence host selection by lepidopteran folivores. Here I describe the studied forest, summarize the history of its infestation by gypsy moth, explain the methods which have been used

TABLE 1. Phytosociological Summary of the Tree Stratum on the Southern Faces of Lake Hill, Mont. St. Hilaire, Québec.

Tree Species	Common Name	Acronym	Frequency ^a /	Density ^b /	Dominance ^c /	Relative Importance Value ^d /
<i>Acer pensylvanicum</i> L.	Striped maple	Apen	1	1	8.5	0.3
<i>A. rubrum</i> L.	Red maple	Arub	1	3	67.7	0.5
<i>A. saccharum</i> Marsh.	Sugar maple	Asac	24	158	2344.4	17.0
<i>A. spicatum</i> Lam.	Mountain maple	Aspic	1	4	39.2	0.5
<i>Amelanchier</i> sp.	Serviceberry	Amel	3	3	27.4	0.9
<i>Betula papyrifera</i> Marsh.	White birch	Bpan	9	47	696.3	5.5
<i>B. lutea</i> Michx. f.	Yellow birch	Blut	1	4	60.7	0.5
<i>Carya cordiformis</i> (Wang)K. Koch	Yellowbud hickory	Carya	2	2	35.6	0.6
<i>Fagus grandifolia</i> Ehrh.	Beech	Fagus	7	78	1373.2	7.6
<i>Fraxinus americana</i> L.	White ash	Frax	17	56	778.5	8.1
<i>Juglans cinerea</i> L.	Butternut	Jug	2	2	71.8	0.7
<i>Ostrya virginiana</i> (Mill.)K. Koch	Ironwood	Ostrya	20	181	1835.3	15.7
<i>Pinus strobus</i> L.	White pine	Pinus	3	4	92.4	1.1
<i>Populus grandidentata</i> Michx.	Big-tooth aspen	Pgran	2	11	206.1	1.4
<i>Prunus pensylvanica</i> L.f.	Pin cherry	Ppen	1	3	27.2	0.5
<i>P. serotina</i> Ehrh.	Black cherry	Pser	2	2	29.0	0.6
<i>Quercus rubra</i> L.	Red oak	Qrub	22	341	6963.8	33.3
<i>Ulmus rubra</i> Muhl.	Slippery elm	Urub	1	1	15.4	0.3
<i>Tilia americana</i> L.	Basswood	Tilia	12	22	357.5	4.7
Summations			131	923	15030.0	99.8

a/ Frequency: The number of 500 m² quadrats in which each tree species occurred; total sample was 24 quadrats.

b/ Density: The number of stems of each tree species found in all 24 quadrats.

c/ Dominance: The cumulative DBH in cm. for each tree species summed in all 24 quadrats.

d/ The mean of frequency, density, and dominance each relativized as a percentage of the respective total for all species; see Curtis (1959).

to quantify host preference, and detail the tree characteristics which were monitored over the period 1979 through 1981. I then present a preliminary analysis of these data and suggest a tentative explanation for the dynamics of the interaction between the gypsy moth and its host plants.

The Lake Hill Study Site

The work described here concerns a gypsy moth infested forest on Mont St. Hilaire, one of the eight Monteregian Hills which rise abruptly from the plains of the St. Lawrence River Valley in the vicinity of Montréal, Québec (Fig. 2). Mont St. Hilaire consists of seven low peaks surrounding a small lake; the peaks rise to a maximum of 416 meters, about 355 meters above the surrounding plain which is a mosaic of villages, agricultural land, and remnant woodland. The mountain itself is covered by forest which in many areas has been little or not at all disturbed for over 300 years; topographic and edaphic heterogeneity contribute to a diversity



Figure 2. Aerial view of Mont St. Hilaire looking southeast toward Rougemont Lake Hill rises from the south shore of Lac Hertel in the center of the figure. Photo courtesy of Dr. Lu Jobin, Laurentian Forest Research Centre, Ste. Foy, Québec.

f habitats including old growth beech-maple forests on deep moist soils, hemlock on steep rocky slopes, yellow birch-red maple swamps in depressions, oak-dominated forests on the dryer sites, and successional forests with aspen and birch on recently disturbed sites (Phillips 1972). Comparable forests have existed in this area for the past 8000 years (Richard 1977). Maycock (1961) provides a thorough summary of the geology, soils, climate, and flora of Mont St. Hilaire and Walther (1963) describes the vegetation of all the Monteregian Hills.

The forest in which gypsy moth activity has been primarily monitored is on the southern and eastern faces of Lake Hill, one of the lower peaks of Mont St. Hilaire which reaches an altitude of only 297 meters. The composition of this forest was determined by randomly placing twenty-four 500 m² circular quadrats along 4 altitudinal isoclines at about 25 m intervals down from the ridge top. In each quadrat the diameter at breast height (DBH) and the species of all trees (DBH \geq 0.8 dm) were recorded. These data are summarized in Table 1. The relative importance values (Curtis 1959) emphasize the dominance of *Quercus rubra*, *Acer saccharum*, and *Ostrya virginiana* in this forest; *Fraxinus americana*, *Fagus grandifolia*, *Betula papyrifera*, and *Tilia americana* are also substantial components of the tree stratum but the remaining eleven tree species are of only minor importance. *Tsuga canadensis*, *Populus tremuloides*, *P. balsamifera*, *P. deltoides* and *Betula populifolia* occur sparsely on Lake Hill but were not found in the random quadrats.

Compared to the forests of the St. Lawrence valley and southern Québec in general (Grandtner 1966; Bouchard and Maycock 1978) the Lake Hill forest is xeric. Detailed studies of the annual heat and water budgets of the south versus north slopes of Lake Hill are available (Rouse and Wilson 1969; Wilson 1970). The oak-dominated forest on the south slope is decidedly more prone to summer drought stress than the beech-maple forest on the north slope. Such topographic juxtaposition of mesic and xeric forest communities is common on the Monteregian Hills (Walther 1963). Xeric forests are generally more susceptible to attack by gypsy moth (Houston and Valentine 1977).

History of Gypsy Moth at Mont St. Hilaire

The gypsy moth appears to have first become established in Québec during the mid-1960's (Cardinal 1967; Brown 1967) and until the mid-1970's serious infestations were limited primarily to Huntingdon and Chateauguay counties south and west of Montréal (Martineau et al. 1975). About 1975 the zone of serious infestation began a steady expansion (Fig. 3); in 1975 traces of gypsy moth were noted on Mont St. Rego, one of the Monteregian Hills south of Mont St. Hilaire (Martineau et al. 1976).

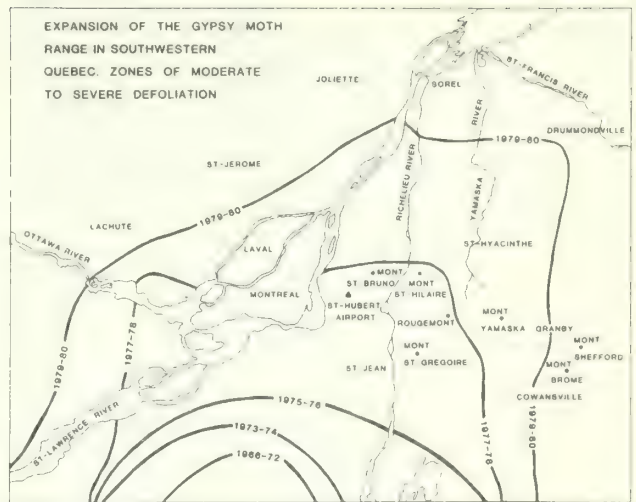


Figure 3. Approximate timing of expansion of the zone of serious gypsy moth infestation in Québec; adapted from information in Brown (1967), Cardinal (1967), Martineau et al. (1975, 1976), Lavalée et al. (1977, 1978), and Lachance et al. (1979, 1980, 1981).

There was no record of gypsy moth, and certainly had been no substantial defoliation, on Mont St. Hilaire until 1977 when 10 hectares of the forest on Burned Hill which is on the southwest face of the mountain were severely defoliated^{1/}. It is likely that the infestation had been newly established only in the preceding few years; this slope of the mountain faces a public campground which may have been the source of infection through vehicular transport from areas to the south or west. By 1978 the infestation had spread to 259 hectares of which 195 were severely defoliated. This area included 123 hectares of the Lake Hill study site most of which was heavily defoliated in 1978. It is noteworthy that serious infestations were limited to the more xeric forests on Mont St. Hilaire in accord with Houston and Valentine's (1977) comments on the characteristics of sites most susceptible to gypsy moth infestations. As part of his doctoral research Madrid (1979; Madrid and Stewart 1981) monitored gypsy moth populations on Lake Hill in 1977 and 1978; his data provide a very useful supplement to my records which do not begin until 1979. In

^{1/} Jobin, L. (1978). Historique et situation actuelle de la spongieuse au Mont St. Hilaire, Internal report, Laurentian Forest Research Centre, Ste-Foy, Québec 13p.

addition government agencies^{2/} monitored the population on Lake Hill in 1978 and also in 1979 (Jobin 1982). Figure 4 summarizes the available information on gypsy moth population density at Lake Hill from 1977 through 1982. It is important to note that the population decline beginning in 1979 was not due to Québec's program of spraying *Bacillus thuringiensis* (Jobin 1982); the Lake Hill study site is on land owned by McGill University and protected as a UNESCO Man and Biosphere Ecological reserve in which spraying has not been allowed.

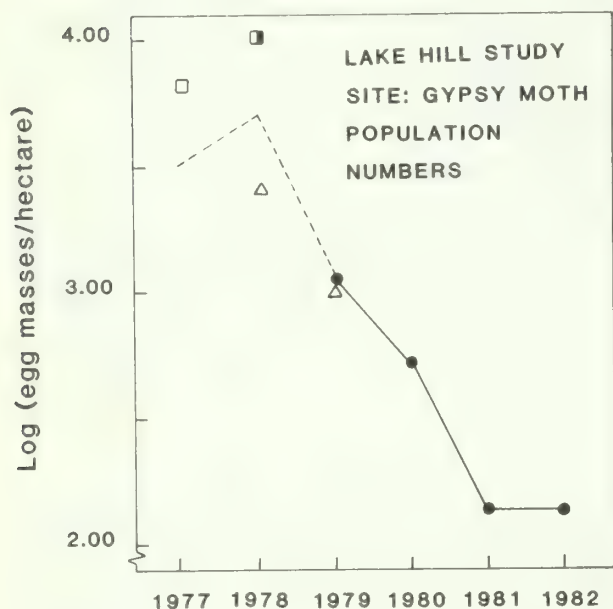


Figure 4. Gypsy moth population dynamics on Lake Hill. The squares are 1977 and 1978 data from Madrid (1979). The 1978 estimate by the government^{2/}, shown as a half-closed square, is virtually identical to that by Madrid. The open triangles are data from Jobin (1982) in 1978 and 1979. All these plots were on the west end of Lake Hill, while my data (closed circles) also include the southern faces of Lake Hill.

Estimates of Gypsy Moth Host Preferences

The host preferences of late instar gypsy moth larvae on Lake Hill have been monitored from 1979 through 1982 using the method des-

cribed in Lechowicz and Jobin (1983). This method measures preference as a function of the availability and the utilization of foliage on the different host trees in the forest. Emphasis is on the host preferences of late instar larvae which are primarily responsible for foliage losses (Valentine and Talerico 1980). If dispersing gypsy moth larvae actually had no preference for or against the foliage of a particular tree they would be expected to feed on that tree in direct proportion to its abundance in the forest canopy. This null expectation is founded on the assumptions that the probability dispersing larvae will encounter a host is determined by the host's relative abundance in the canopy and that larvae without preferences will settle on the first host they encounter. At dispersal larval preferences in the field should be closely related to the preferences reported in the behavioral literature which are determined in laboratory choice-trials (Mosher 1915; Barbosa *et al.* 1979). The late instar preferences reported here, however, arise not only from behavioral choices during dispersal but also from possible differences in early instar survival on different hosts. Larval survival may be controlled not only by foliage quality but also by bark roughness, canopy architecture, and similar traits that influence vulnerability to predators and parasites. These late instar host preferences are perhaps best viewed as measures of host susceptibility to defoliation by gypsy moth.

As discussed in detail by Lechowicz and Jobin (1983), the availability p_i for host i is measured by its contribution to the total DBH of the m different hosts in the sampled forest:

$$p_i = \frac{\sum_{j=1}^{n_i} b_{ij}}{\sum_{i=1}^m \sum_{j=1}^{n_i} b_{ij}} \quad \text{eq.1)}$$

where b_{ij} is the DBH of the j th tree of species i . Utilization is estimated from the mean of repeated counts of numbers of late instar larvae congregating under tarpaper bands around each tree in the sampled quadrats; this is a standard method to estimate numbers of late instar larvae feeding on a tree (Weseloh 1974). This estimate assumes that late instar migration between trees does not occur during the counting period; in low density populations this assumption appears to be met (Lechowicz and Jobin 1983; Mauffette and Lechowicz^{3/}; Wallner, this volume). The utilization u_i of host i is measured by the number of larvae on host i relative to the total number of larvae on all the sampled hosts:

^{2/} Bordeleau, C., C. Gagnon, C. Theriault, L. Jobin, C. Coulombe, and A. Caron (1980). Evaluation du programme de traitement au B.T. effectué contre la spongieuse au Québec en 1979, Internal Report, Ministère de l'Agriculture, Québec 37p.

^{3/} Mauffette, Y. and M.J. Lechowicz. The influence of host plant on the larval development rate of gypsy moth, *Lymantria dispar* (L.), in the forest environment, manuscript in review.

$$\bar{r}_i = \frac{\sum_{j=1}^{n_i} l_{ij}}{\sum_{i=1}^m \sum_{j=1}^{n_i} l_{ij}} \quad \text{eq. 2)}$$

where l_{ij} is the mean number of larvae counted on the j th tree of species i .

Since gypsy moth larval growth and development differs on different host species (Schmidt 1956; Barbosa and Capinera 1977), the timing of larval counts to achieve a representative estimate of \bar{r}_i is important. If a count is taken too early, larvae on some hosts will not have reached instar IV when the diurnal resting behavior on which the tarpaper counts depend begins (Leonard 1970). Conversely counts taken too late will miss larvae that have already pupated. Mauffette and Lechowicz³ have analyzed the time course of larval numbers on 29 host species at 13 sites in southwestern Québec; in general there is about a 2 to 3 week window during which the mean of repeated counts will provide a representative estimate of late instar larval numbers across host species. It is desirable to make a fairly long series of counts and then discard the early and late entries which indicate that resting behavior is not developed on all hosts or that substantial pupation has occurred on some hosts. The preferences reported here are based on counts made on June 26-27 and July 3-4, 1979; on June 22 and 30, 1980; on June 21, June 29, and July 5, 1981; and on June 22, June 30, July 6 and July 14, 1982.

Several different algorithms are available to calculate preference from these measures of availability and utilization (Lechowicz 1982). Most give comparable results and differ primarily in convenience of interpretation. Here I have used Vanderploeg and Scavia's (1979a, 1979b) E^* electivity index and their related selectivity index W . The selectivity for tree species i is:

$$W_i = (\bar{r}_i / p_i) / \sum_{i=1}^m (\bar{r}_i / p_i) \quad \text{eq. 3)}$$

and the electivity for species i is:

$$E_i^* = (W_i - 1/n) / (W_i + 1/n) \quad \text{eq. 4)}$$

where n is the number of potential host species. The selectivity W ranges from zero to one, a useful property in certain statistical analyses but not clearly indicative of preferred versus avoided hosts. In general, as a summary preference index, the E^* electivity is easiest to interpret: E^* is zero if the larvae feed randomly on a host, approaches minus one the more they avoid a host, and plus one the more they prefer a host. Lechowicz (1982) discusses the interrelationships and properties of all the available preference indices.

Monitoring of Host Foliage Characteristics

Many foliage characteristics have been im-

plicated as possible factors determining the favorability of trees as hosts to lepidopteran folivores. Investigators have tended to focus on only one or a few factors in a given study despite the likelihood that a number of factors interact to control the susceptibility of a tree to herbivore attack. Certainly no single factor has proven to be even a reasonably universal predictor of herbivore susceptibility in woody plants. Also the predictable correlations between certain traits that may arise from constraints imposed by tree physiology and architecture can only be understood in a multifactorial analysis. Therefore within logistic limitations we have attempted to monitor a comprehensive set of foliage characteristics (Table 2) that may play a role in host selection by the gypsy moth. Sampling was concentrated on the spring foliage coincident with dispersal of gypsy moth and on the mid-summer foliage available to the late instar larvae. Samples were taken from a total of 23 tree species on Lake Hill but only 14 species both having adequate replication (3-6, mostly 5 or 6) and having been included among the 19 species in the quadrats analyzed for host preference patterns are reported here. In the following paragraphs I briefly rationalize my choice of foliage characteristics and describe the methods used to assay them.

Leaf Toughness

Feeny (1970) demonstrated that the peak numbers of lepidopterans feeding on oak foliage coincided with the availability of tender, young leaves in the spring. For gypsy moth Hough and Pimental (1978) showed that larvae develop less well on the older, tougher leaves of host trees. Consequently toughness was monitored by Feeny's (1970) method which measures the mass required to shear the leaf tissue in an area between the main veins of the leaf. The shearing face of the penetrometer was 0.145 cm^2 . In 1979 sand was used to add mass but subsequently water delivered through a pipette tip was found to give more reproducible results. Four replicate measurements of toughness were made on freshly harvested leaves.

Leaf Water Content

Scriber and Feeny (1979) have shown a correlation between higher leaf water content and better larval growth in lepidopteran larvae feeding on leaves of woody plants. Scriber and Slanksky (1980) review the importance of water content in effecting insect growth. The results of Hough and Pimental (1978) on gypsy moth larvae also indicate the favorability of high water content. The fresh and oven-dry weights of newly harvested leaves were used to calculate water content as a percentage of fresh weight at harvest; this is the normal practice in the entomological literature in contrast to the expression of water as a % dry weight common in the botanical literature.

Table 2. Foliage characteristics monitored from 1979 through 1981 at Lake Hill on Mont St. Hilaire, Québec. Rows designate date and Julian day of actual samples and the tabled entry indicates how samples were combined to represent spring or summer leaf condition in each year. Unsampled characteristics are indicated by n.d. In addition daily phenological records were kept in 1980 and 1981 during the period of canopy development.

	<u>Toughness</u>	<u>% Water</u>	<u>% Nitrogen</u>	<u>Folin-Denis Phenolics</u>	<u>Precipitable Tannins</u>	<u>Leucoantho- cyanins</u>	<u>Leaf pH</u>	<u>Leaf Buffer Capacity</u>
<u>1979</u>								
May 14 (Day 134)	spring	spring	spring	spring	n.d.	spring	n.d.	n.d.
May 21 (Day 141)	spring	spring	spring	spring	n.d.	spring	n.d.	n.d.
June 4 (Day 151)	spring	spring	spring	spring	n.d.	spring	n.d.	n.d.
July 18 (Day 199)	summer	summer	summer	summer	n.d.	summer	n.d.	n.d.
<u>1980</u>								
May 27 (Day 148)	spring	spring	spring	spring	spring	spring	spring	spring
June 18 (Day 170)	summer	n.d.	n.d.	summer	n.d.	summer	n.d.	n.d.
July 16 (Day 198)	summer	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
<u>1981</u>								
June 1 (Day 152)	spring	spring	spring	spring	spring	spring	spring	spring

Leaf Nitrogen Concentration

McNeil and Southwood (1978) and Mattson (1980) review the considerable support for the critical importance of nitrogen availability to the growth of lepidopteran larvae feeding on the foliage of woody plants. The nitrogen concentration of oven-dry leaves was determined by a Kjeldahl analysis for total organic nitrogen (Bradstreet 1965) involving a sulfuric acid digestion in the presence of selenium catalyst and K_2SO_4 without any predigestion to reduce inorganic nitrogen. The resulting digest was then Nesslerized (Middleton 1960) and assayed colorimetrically for ammonia. Pace et al. (1982) have reported problems with nitrate reduction even in the normal Kjeldahl digestion but since tree leaves are extremely low in inorganic nitrogen (Van Tuil 1965) the nitrogen assayed here should be only that in forms available to lepidopteran larvae.

Leaf Concentrations of Various Phenolic Compounds

Many authors have taken the view that phenolic compounds function as important defenses against folivores, especially in woody plants (see particularly the reviews by Levin 1971; Feeny 1976; Swain 1978; Rhoades 1979; and Futuyma 1983). This view has not gone unchallenged, particularly by those who emphasize the many metabolic roles of phenolic compounds (Seigler and Price 1976) and those who question the efficacy of such putative defenses (Fox and McCauley 1977; Bernays 1978; Moran and Hamilton 1980; Martin and Martin 1983). This debate is

aggravated by the extreme chemical diversity of phenolic compounds (Ribereau-Gayon 1972; Swain 1979) and the inadequacies of available assays for different groups of phenolic compounds. The latter problem has been recently reviewed but without a fully satisfactory conclusion (Horvath 1981; Martin and Martin 1982; Tempel 1982). Despite these problems, the unresolved controversy on the role of at least some types of phenolic compounds as defenses against herbivores requires their consideration here.

In the face of current methodological problems, I have settled on three assays for different phenolic fractions likely to have interpretable relationships with observed gypsy moth activity: 1) a Folin-Denis assay for total phenolics (Rosenblatt and Peluso 1941; Swain and Hillis 1959), 2) a leucoanthocyanin assay for condensed tannins (Swain and Hillis 1959 as modified by Govindarajan and Mathew 1965), and 3) a newly developed assay for phenolic compounds that bind to isinglass, a partially purified collagen from fish swim bladders often used to remove phenolic impurities from wine. The first two assays are well established. The isinglass assay is related to traditional tannin assays in the leather industry (Horowitz 1970), Marigo's (1972) absorption on gelatin, or Martin and Martin's (1982) recent modification of Bate-Smith's (1973) hemeanalysis. In all these methods Folin-Denis assays are made on an extract before and after exposure to a test protein to which tannins will bind, hopefully leaving only simple phenolics in solution. The difference in initial and final absorbance is then taken as a measure of biologically active tannins. Ideally the binding substrate should be

leaf protein from each of the tree species being studied (Martin and Martin 1983) but this is virtually impossible in most studies. Recent discussions (Martin and Martin 1982; Tempel 1982) agree that at least some type of precipitable tannin assay should be included in ecological studies because such an assay directly measures the ability of tannins to bind protein, the supposed basis of their role in plant defense. In all three of the assays used here I have expressed results as simple absorbance values for lack of appropriate calibration standards (Martin and Martin 1982). This does raise the practically unavoidable possibility in this cross-species comparison that absorbance will not be an unbiased quantitative index of actual phenolic concentrations because of qualitative differences in the absorption spectra of constituent phenolics on the different tree species.

One further aspect of these phenolic assays which has received too little consideration in the literature is the method of extraction of phenolic compounds from harvested leaf tissues. It is clear that different extraction solvents will differ in both the quantities and quality of phenolic compounds recovered (Ribereau-Gayon 1972). In 1979 we extracted 0.1 gr oven-dry (70-80°) weight of powdered leaf tissue with an 80% methanol acid 1% HCl solution for 24 hours in a Soxhlet apparatus. In subsequent years the method of Swain (1979) was adopted in which 0.1 gr oven-dry (40-50° to lessen degradation of compounds during drying) weight of powdered leaf tissue was extracted three times in hot (80°) 80% methanol. Test extractions of fresh frozen rather than dried leaf tissue did result in higher absorption per unit dry weight in both the Folin-Denis and leucoanthocyanin assay but the readings were significantly positively correlated (FD: $r = 0.26$, $p = 0.029$; LA: $r = 0.35$; $p = 0.003$). The problems and potential errors inherent in taking truly parallel samples to estimate the equivalent dry weight of frozen samples makes the direct assay of dry tissue preferable in this comparative study.

Leaf pH and Buffer Capacity

Berenbaum (1980) has shown that caterpillar species feeding on leaves of woody plants have higher gut pH than those feeding on herbaceous plants. She reported a mean midgut pH of 8.67 for larvae feeding on woody plants, significantly higher than the pH 8.29 mean for species feeding on herbaceous foliage. She suggested that the high gut pH of caterpillars feeding on woody plant foliage would serve to break up tannin-protein complexes thus rendering the tannin-based leaf defenses postulated to be widespread in woody but not herbaceous plants less effective. On a dry weight basis the hydrolyzable tannins are considerably more effective at complexing with proteins than the condensed tannins (Swain 1978), but the hydrolyzable tannin-protein complexes are less stable than those formed by condensed tannins (Goldstein and Swain 1965). Dissociation of the

tannin-protein complex occurs rapidly above pH 8 for condensed tannins and above pH 5 for hydrolyzable tannins (Loomis and Battaile 1966; Martin and Martin 1983). Thus high gut pH could conceivably increase the leaf nitrogen available to caterpillars feeding on woody plant foliage.

If this hypothesized mechanism is important in mediating the caterpillar-host tree interaction, trees that have lower leaf pH and/or higher leaf buffer capacity should be less preferred as hosts. Caterpillars would incur greater metabolic costs in maintaining their high gut pH to effectively digest more acidic and/or better buffered leaf tissue and should therefore tend to avoid such host foliage. To test this hypothesis I measured both the pH of freshly homogenized frozen leaf tissue and its buffer capacity as the μ moles NaOH necessary to bring the aqueous homogenate to pH 8.75.

Leaf Phenology

The temporal coordination of herbivore and host life cycles is obviously important, especially in insects like the gypsy moth which break diapause in concert with the emergence of the tree leaves on which they feed. Barbosa et al. (1979) have suggested that differences in tree phenology may influence susceptibility to attack by gypsy moth larvae. To test this hypothesis we made daily observations of canopy development on each tree from which leaves were harvested^{4/}. Here the mean of the day a tree's first buds burst and the day 90% of its leaves had expanded was taken as a measure of the timing of its spring canopy formation.

Other Possible Factors

A considerable number of additional factors that might have some influence on gypsy moth host selection were not considered in these initial experiments. In some cases factors were rejected as of little or no importance on the basis of available evidence. Foliage concentrations of P, K, Mg, Na, Al, Ba, Fe, Sr, B, Cu, Zn, or Mn are unrelated to gypsy moth growth and fecundity (Barbosa and Greenblatt 1979; Valentine et al. 1983). Similarly variations in foliage concentrations of 25 amino acids were not correlated with gypsy moth success (Valentine et al. 1983). These investigators do report significant positive regressions of pupal weight on total free sugars and free sugar:Ca ratios; but the ranges in sugar and Ca concentrations sampled were based on both defoliated and undefoliated trees - other factors may well have contributed to these observed correlations. Most earlier reports (Beck and Reese

^{4/} Lechowicz, M.J. The phenology of leaf emergence in a northern deciduous forest, manuscript in preparation.

1976; Scriber and Slansky 1981) indicated that foliage carbohydrate concentrations are adequate to meet insect requirements. Nonetheless, as discussed subsequently, some carbohydrate fractions may provide token cues important in host selection and, considering the recent results of Valentine et al., the possible importance of carbohydrates in gypsy moth nutrition cannot be dismissed.

Gypsy Moth Host Preferences at Mont St. Helaires: 1979-1982

The larval host preferences of gypsy moth in the Lake Hill forest were generally stable during the decline of the outbreak in 1979 and 1980 (Fig. 5). Populus grandidentata, Quercus rubra, Ostrya virginiana, Amelanchier spp., and Acer saccharum were consistently preferred as larval hosts while Tilia americana, Carya cordiformis, Prunus pensylvanica, Fraxinus americana, Acer pensylvanicum, and Prunus serotina were consistently avoided. With the exceptions of Fagus grandifolia and Betula papyrifera, trees that had erratic electivity values during 1979-80 were poorly replicated in the available samples - Acer rubrum or Juglans cinerea, for example. The apparent drop in preference for beech in 1980 arises in part from a localized outbreak of nuclear polyhedrosis virus in a single quadrat; the increasing preference for white birch is an interesting but unexplained trend. In general the host preferences during this period of relatively high larval numbers are in accord with the earlier American and European reports reviewed by Lechowicz and Jobin (1983).

In 1981-82 when larval numbers had dropped to innocuous levels, there were some marked shifts in larval preference. Only Populus grandidentata was consistently strongly preferred over the 1979-82 interval. Quercus rubra and Ostrya virginiana, although still preferred, had lower electivity values in 1981 which returned toward their 1979-80 levels in 1982. Amelanchier dropped abruptly to being a slightly avoided host and Acer saccharum declined steadily to also being avoided in 1982. In contrast Fagus grandifolia which had been an avoided host became slightly preferred and Betula papyrifera had risen steadily until it was only slightly avoided. Most hosts avoided in 1979-80 such as Tilia americana and Fraxinus americana were even less preferred by the endemic larval population in 1981-82. There is some indication here that the few most preferred hosts are more heavily used by an endemic population and that the most avoided hosts are especially little used. Intermediate hosts seem to undergo shifts to greater or lesser preference that may potentially be explained by changes in foliage quality. It should be clearly recognized that even at innocuous population levels the gypsy moth population maintains a high degree of polyphagy with virtually all host species attacked to some degree.

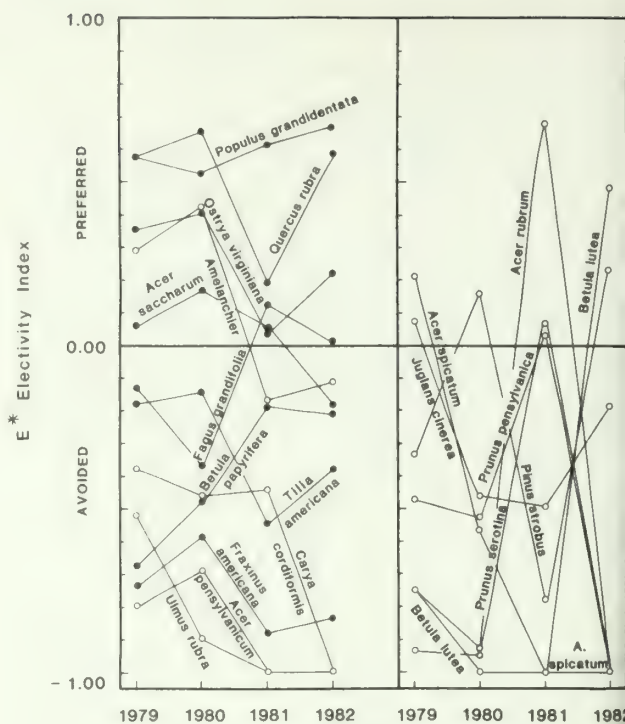


Figure 5. The host preferences of late instar larvae in the Lake Hill forest from 1979 through 1982. The calculations have allowed for occasional missing data; open circles represent electivity values based on fewer than 6 trees. Most of the poorly replicated host species are plotted in the right graph to avoid confounding the interpretation of trends in the generally better replicated species in the left graph.

Because of the inability of female gypsy moth adults to fly and the limited mobility of dispersing larvae (Mason and McManus 1981), these shifts in larval preferences may be explained in part by patterns of egg deposition rather than simply larval dispersal and host selection. It is useful to compare the observed electivities for numbers of egg masses on a host (calculated analogously to that for larvae) to the larval host preferences (Fig. 6). In general more preferred larval hosts also bear a greater proportion of the egg masses in the forest; this is not particularly surprising considering that selection should favor larval preferences for hosts which will allow successful survival and reproduction. It does suggest that late-instar migration to avoided larval hosts for pupation (Rossiter 1980; Mauffette and Lechowicz^{5/}) plays only a minor role in the population dynamics of gypsy moth on Lake Hill. On the other hand the cyclic tendencies apparent in the relationships between egg and larval host electivities supports the suggestion that changes in foliage quality may influence larval

host preferences. Consider, for example, *Quercus rubra* which had high larval and egg electivity in 1979; in 1980 larval activity was even slightly higher but egg electivity was sharply reduced. This reduction is reflected in a lowered larval electivity in 1981 but increased egg deposition. In turn by 1982 both larval and egg electivities have returned to 1979 levels. Such cyclic patterns raise the possibility that changes in foliage quality including induced responses such as those shown for birch, oak, and maple (Haukioja and Niemela 1979; Wallner and Walton 1979; Schlichting 1980; Schultz and Baldwin 1980) may influence the gypsy moth population dynamics on host trees from year to year.

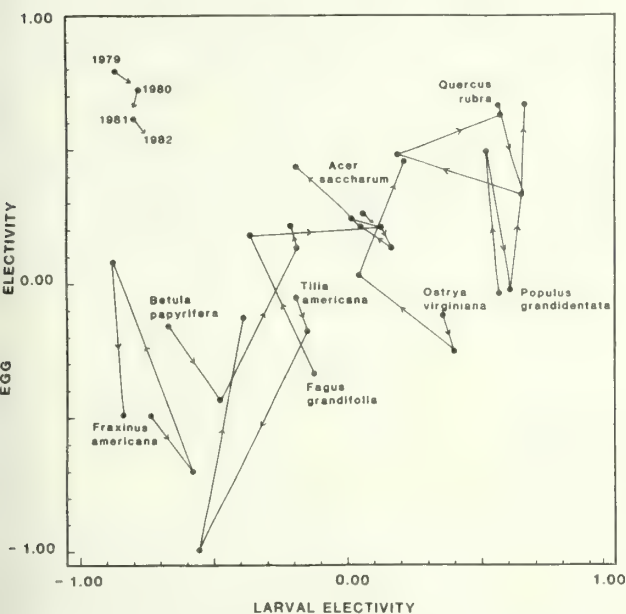


Figure 6. Electivity for egg masses versus that for late-instar larvae in the Lake Hill forest during 1979 through 1982. Trends are shown only for the eight well-replicated host species although all sampled hosts were used to calculate the electivities.

Foliage Characteristics at Mont St. Hilaire: 1979-1982

A multivariate approach to preliminary analyses of the gypsy moth host interaction. It is not possible in this paper to present the detailed results of all the assays of foliage quality in relation to gypsy moth host selection. Instead I have used a multivariate statistical technique that can most concisely be called biplot analysis (Gabriel 1971) to sum-

marize the primary interrelationships between the measured foliage characteristics. Biplot analysis begins with a matrix of rows of objects described by columns of their attributes, in this instance 14 tree species characterized by their mean values for the traits in Table 2. The matrix is first relativized by dividing all entries by the maximum value in their respective columns. The relativized matrix is then centered by subtracting the respective column mean from each entry; this results in comparison of all tree species to a hypothetical, mean tree species. Finally this relativized and centered matrix is analyzed by canonical decomposition, a generalization of singular value decomposition, to acquire the best possible representation in few dimensions of the information in the multi-dimensional input matrix (see details in Gabriel 1971). The reduced matrix can then be represented graphically in two (hence biplot) or three dimensions to aid interpretation of trends in the data.

In interpreting a biplot such as that of the foliage traits analyzed here (Fig. 7) a number of general rules should be borne in mind. First consider the locations of the individual host species in the two-dimensional graph. Recall that the analysis is centered on a hypothetical mean host plotted at the origin - the dispersion of tree species around the origin is a graph of variation among hosts based on their foliage characteristics. Trees that are closer together are more similar than those further apart on the basis of the foliage traits used in the analysis.

Perhaps the most useful quality of the biplot compared to a technique like principal component analysis (Seal 1964) to which it is closely related is that unlike PCA the biplot also directly illustrates the contributions of individual traits in determining the relationships between trees. For convenience the traits are represented by vectors originating from the origin. The longer a vector, the more variable is that trait among the sampled trees - note however that small differences in a relatively invariant trait may still have important biological effects. The biplot shows only the pattern of variability in traits, the investigator must interpret that variation biologically.

Not only the length but also the direction of the trait vectors in the biplot are important aids to biological interpretation. The cosine of the angle between any two vectors approximates their correlation. Thus acute angles suggest positive correlation and obtuse angles negative correlation; trait vectors at right angles are uncorrelated.

Finally when any vector is extended across the biplot as an axis, the projections of tree species on that axis rank the trees from low to high in regard to that trait in the direction the vector points. In other words the vectors point in the direction that trees with high values of their respective traits will be dis-

/ Mauffette, Y. and M. Lechowicz. Utilization of the larval host tree as a pupation site by the gypsy moth, *Lymantria dispar* L. (Lepidoptera: Lymantriidae), manuscript in review.

placed in the biplot; the actual placement of the tree species arises from the interaction of all the traits which "pull" the species in different directions with different strengths depending on its foliage characteristics.

A cautionary note is in order: like many other multivariate techniques, biplot analysis cannot fully represent all the information in a complex matrix in only a few dimensional graph. The accuracy of the interpretations just described hinges on the amount of variance in the original matrix represented in the biplot. Two vectors apparently highly positively correlated may, for example, actually diverge at a right angle in the third dimension. For this reason biplot analysis can only be an exploratory technique to provide initial help in puzzling out complicated and little known biological situations. It must be supplemented by careful scrutiny of actual correlation coefficients between traits and by traditional graphic comparisons of interrelationships between selected traits. As an exploratory technique biplot analysis can only suggest, not test, hypotheses. Given the large number of interacting traits which may influence gypsy moth host selection it does

provide a useful and needed overview which helps focus future research on specific hypotheses involving fewer traits.

Biplot of Foliage Quality

The biplot of foliage traits alone (Fig. 7) emphasizes that many traits implicated in plant defense have fairly stable interrelationships with one another from year to year. For example, the suite of traits involving leaf acidity, buffer capacity, total phenolics, and precipitable tannins is notably stable both in spring and summer and from year to year. Trees with more acidic leaves tend to be consistently higher in total phenolic concentrations. Foliage toughness and water content are generally negatively correlated suggesting that these traits which have usually been considered separately in the entomological literature may better be combined as a single measure of leaf sclerophylly. Leaf nitrogen concentration remains relatively stable over time; although the correlations are weak, less sclerophyllous and less acidic leaves tend to be richer in nitrogen. Time of leafing out varies relative

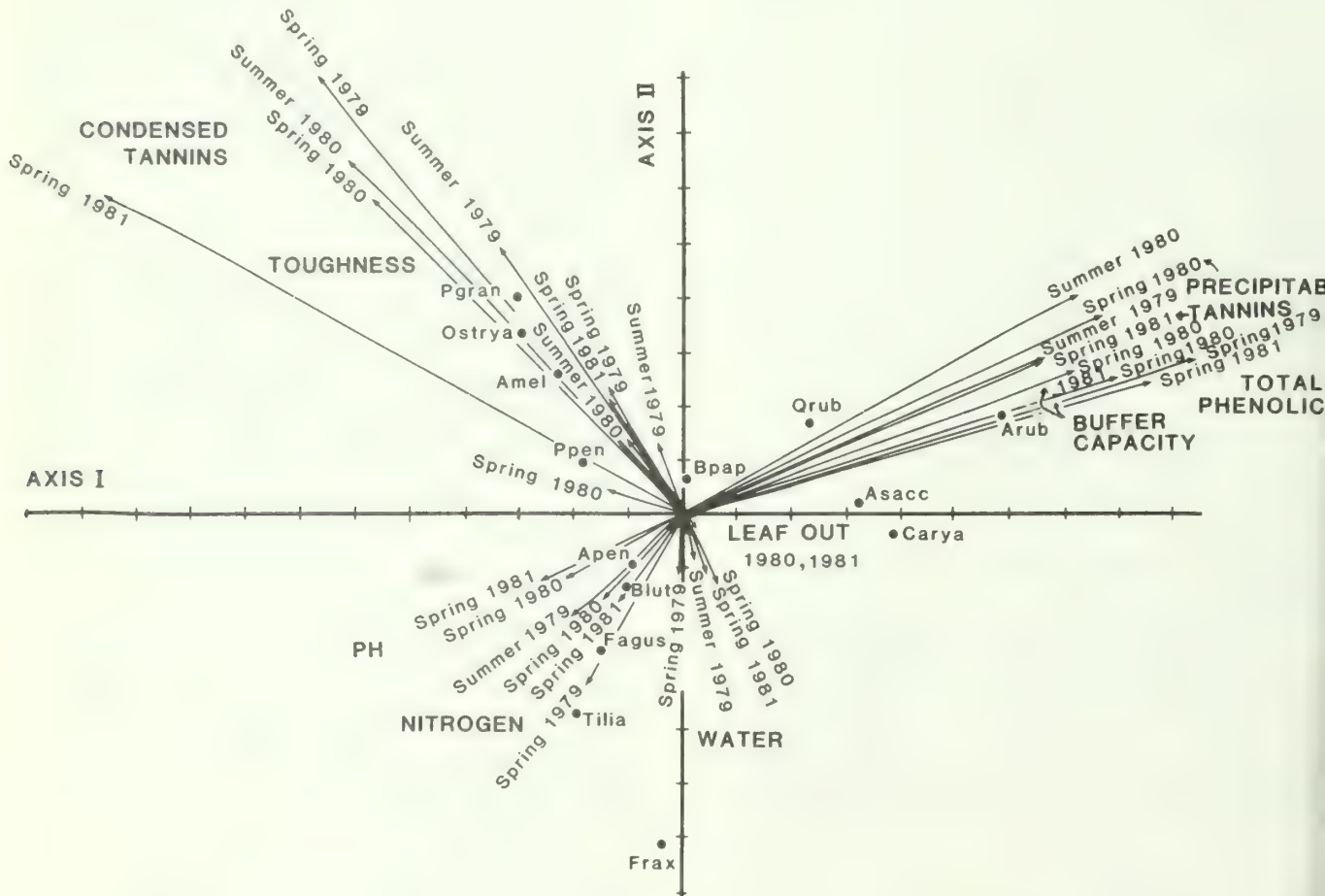


Figure 7. Biplot of mean foliage characteristics for 14 tree species in the Lake Hill forest. The two axes account for 70% of the variance in the relativized data matrix. See text for explanation of how to interpret this graph.

title among the 14 tree species on Lake Hill; actual values have a range of only 8 days in 1980 and 17 in 1981.

The annual pattern in condensed tannin concentrations is in contrast to the generally stable correlations among these other foliage characteristics. Only total phenolics and precipitable tannins approach condensed tannins in terms of variation between trees. Unlike these other highly variable traits, condensed tannins also showed an interesting pattern of annual variation. During the outbreak year 1979 and 1980 the pattern of condensed tannin levels between tree species was similar and condensed tannins were higher in sclerophyllous leaves (Fig. 7). In 1981 as the gypsy moth population reached innocuous levels there was a shift in its pattern of condensed tannins in the spring leaves of the different host trees.

The host trees themselves fall along two general axes of variation in terms of the traits measured: 1) coordinated variation in a syndrome of traits involving highly intercorrelated changes in acidity, buffer capacity, total phenolics, precipitable tannins, and nitrogen and 2) in another syndrome involving toughness, water content, and condensed tannins. The distribution of tree species in the biplot suggests two relatively distinct modes of leaf phenolic metabolism. Some trees like *Populus grandidentata*, *Ostrya virginiana*, and *Amelanchier* are set apart by their relatively high concentrations of condensed tannins while others like *Acer rubrum*, *A. saccharum*, *Carya cordiformis*, and *Quercus rubra* have relatively low condensed tannin concentrations but high total phenolics and precipitable tannins. The general validity of these trends and their possible relevance to different modes of defense against folivores merit further consideration.

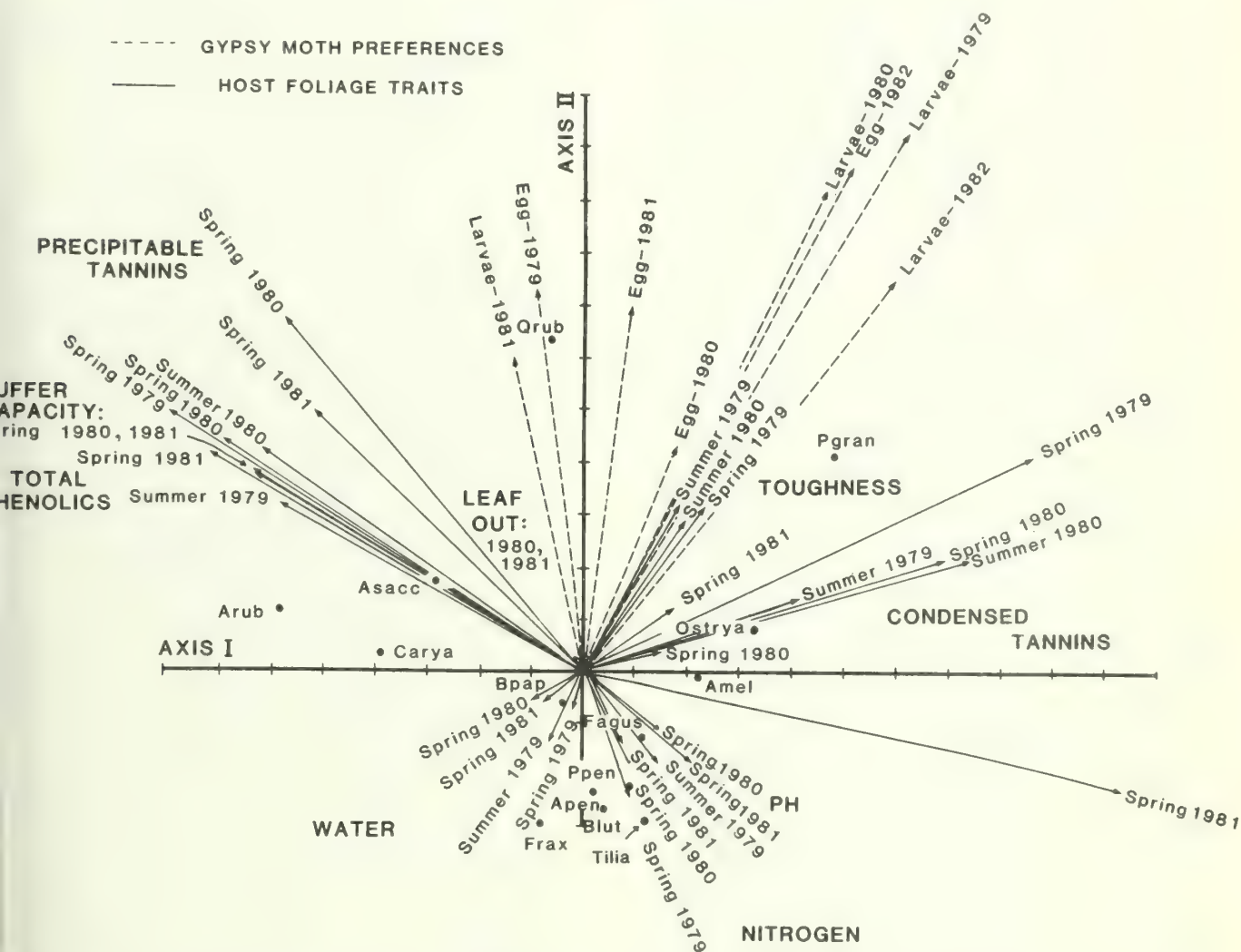


Figure 8. Second biplot including not only the plant traits in the preceding analysis (Fig. 7) but also the 1979 through 1982 larval and egg selectivities for the 14 host trees. Because interpretation of the biplot used here becomes difficult when a trait takes both positive and negative values, the selectivity W rather than the E* selectivity values were used in this analysis. Lechowicz (1982) showed that W and E* are very highly correlated. The two axes account for 61% of the variance in the relativized data matrix. See text for further discussion.

Relationships of Gypsy Moth Activity to Foliage Quality

A second biplot (Fig. 8) adding the 1979 through 1982 larval and egg selectivity data for the 14 tree species to that on foliage quality was run to explore the correlations between these plant traits and the patterns of gypsy moth host preference. This biplot retains the underlying relationships of the plant traits among themselves. The two major axes of plant variation involving condensed tannins versus precipitable tannins and total phenolics are still apparent. Precipitable tannins, however, appear to be somewhat more associated with gypsy moth preferences than the other plant traits involved in the same syndrome of variation. Similarly sclerophylly, particularly in the summer, appears more associated with gypsy moth preferences than the concentrations of condensed tannins. Leaf pH, buffer capacity, total phenolics, and nitrogen appear to be only weakly or not at all related to larval host preferences. Although leaf phenology varies relatively little among hosts there is some indication that larvae may prefer hosts that leaf out later. In general this biplot suggests that dispersing gypsy moth larvae prefer trees that later in the season will have tough, dry leaf tissues and that these preferences may be modified in part by leaf concentrations of condensed and, to a lesser degree, precipitable tannins in the spring and early summer.

The actual distribution of host trees in the biplot also indicates that gypsy moth host preferences are not simply and entirely determined by the observed plant traits, but are also influenced by traits not included in this data set. For example, the two most consistently preferred hosts, Quercus rubra and Populus grandidentata, represent the two different syndromes of leaf types in the biplot of plant traits alone (Fig. 7). It is not immediately apparent what these two hosts have in common that leads to their being attacked preferentially by gypsy moth. Quercus rubra in particular is singled out as highly preferred from among trees like Acer saccharum, A. rubrum, and Carya cordiformis to which it is very similar in terms of the observed foliage traits. The biplot (Fig. 8) thus suggests that factors other than those traditionally supposed to determine susceptibility to herbivore attack among trees are important in gypsy moth host selection.

A Model of the Gypsy Moth-Host Tree Interaction

The diverse observational data analyzed here have allowed elimination of certain plant traits as uncorrelated with gypsy moth preferences and therefore unlikely to be important factors in host selection. On the other hand, although no clear and simple explanation of host selection has emerged, certain plant traits are implicated as factors involved in determining the probability that a tree will be attacked by gypsy moth. The recognition of such key traits

in this exploratory analysis raises a number of hypotheses which require experimental tests. As a framework for continuing studies I have summarized these hypotheses in a tentative model of gypsy moth host selection which is explained below. The model has two main tenets: 1) that dispersing gypsy moth larvae preferentially settle on trees with higher sugar:tannin ratios in their young foliage and 2) that stress-induced variations in the sugar and tannin concentrations of young foliage can lead to year to year variation in a tree's susceptibility to attack by gypsy moth.

On a regional basis, the forests most susceptible to infestation by gypsy moth occur on more arid, nutrient-poor sites (Houston and Valentine 1977) where sclerophyllous tree species are most frequently found. Within these susceptible forests, host trees with more sclerophyllous mature foliage appear from the present analysis to be preferentially attacked by gypsy moth larvae. This positive association between sclerophylly and the host preferences of gypsy moth provides a useful clue to the possible basis of host selection by this polyphagous folivore.

Sclerophylly has long been associated with both arid, nutrient-poor environments and low rates of carbon fixation (Small 1973; Seddon 1974). Sclerophylly is believed to improve survival during the relatively frequent periods of stress typical of such habitats but at the expense of reduced productivity when conditions are favorable. In general we might expect the less productive sclerophyllous tree species to have more limited resources to allocate to defenses against folivores. In addition the leaves of sclerophyllous trees tend to develop more slowly in the spring (Federer 1976). Thus gypsy moth larvae feeding on the spring and early summer foliage of a sclerophyllous host may enjoy a relatively longer period of access to higher quality, immature foliage; models of gypsy moth larval development (Valentine and Talerico 1980) suggest that selection of hosts offering even slightly longer periods of favorable foliage availability can improve larval survival and fecundity. Host trees that later in the summer are most sclerophyllous and then apparently lowest in foliage quality may actually have provided the longest periods of immature foliage most favorable for larval development.

How then might dispersing larvae recognize the sclerophyllous hosts offering such a favorable opportunity for larval development? During larval dispersal all the available foliage is relatively tender and moist and there are no consistent correlations between the sclerophylly of young and old foliage; some cue other than sclerophylly itself must be used by the dispersing larvae. Soluble sugars, especially sucrose, which are known to be an important feeding stimulus in very many insects (Dethier 1982) seem the most likely proximate control on host selection by dispersing gypsy moth larvae. Transport of soluble sugars to developing tree

leaves is high (Dickson and Larson 1981) and could continue longer in the more slowly developing sclerophyllous species. Depending in part on the relative timing of eclosion and bud break, dispersing larvae will thus be more likely to encounter sugar-rich foliage on the lower-developing, sclerophyllous hosts. Further study is necessary to test this hypothesis that soluble sugar concentrations in host foliage during dispersal actually determine host selection.

Further investigations should also consider the possible interaction between soluble sugar and tannin concentrations. Dethier (1982) has reported that although gypsy moth larvae cannot sense tannic acid per se, this hydrolyzable tannin does suppress the larvae's electrophysiological response to sugars. Perhaps tannins alter the apparent levels of soluble sugars in the young foliage available to dispersing larvae. If this is the case we may hypothesize that gypsy moth preferentially attack trees that have high sugar:tannin ratios in their young foliage.

Tannins present in young foliage during larval development may also influence year to year trends in the numbers of dispersing larvae that potentially settle on different host trees. Because of the limited vagility of the later instars and female adults of the gypsy moth (Doane and McManus 1981; Wallner, this volume), any reduction in foliage quality on attacked trees will act to limit larval success on that tree and thereby reduce the local density of dispersing larvae the next year. Data on lepidopteran larvae including the gypsy moth (Feeny 1968; Karasov and Satarova 1973) have shown that tannins can reduce foliage digestibility. High tannin levels in the young foliage critical for larval development can thus reduce egg deposition by female larvae on these hosts. If in addition elevated levels of tannins can be maintained in young foliage the next spring, then the preference of dispersing larvae for the host may be further reduced by suppression of the neurophysiological response to sugar stimuli as hypothesized above. The maintenance of high tannin levels, however, depends on the availability of photosynthetic reserves which will tend to be lower in more sclerophyllous hosts. Sclerophyllous hosts will therefore tend to be more susceptible to sustained infestations of gypsy moth larvae from year to year. Moreover, productive hosts better able to either constitutively or facultatively maintain high levels of tannins in their spring foliage could actually shift large numbers of dispersing larvae to the less well-defended, sclerophyllous hosts. It is through mechanisms such as these that the gypsy moth preference for more sclerophyllous hosts may be expressed and maintained.

This model is in accord with the recent revival and elaboration (Haukioja 1980) of the idea that climatic stress on host plants can release a serious outbreak of insect herbi-

vores. When all trees have been weakened by a stress such as a severe drought, limited reserves of photosynthate may be diverted from defense to other more essential functions. The polyphagous and widely dispersed gypsy moth larvae in the subsequent spring then would find an unusually high number of favorable host trees apparently high in sugar content for lack of masking tannins. Larval success on these drought stressed trees would be relatively high and defoliation would thus reduce the recovery of photosynthate resources even if climatic conditions were again favorable. Gradually enhanced defenses, probably aided by predator and pathogen attacks on gypsy moth (Doane and McManus 1981), would reduce the larval numbers to low enough levels for the normal patterns of leaf development and defense to prevail. The endemic gypsy moth population then would again preferentially attack the more sclerophyllous hosts which are generally less able to maintain effective tannin-based defenses and have the longer leaf development times favorable to gypsy moth larval success.

The model proposed here can potentially explain two key aspects of the gypsy moth-host interaction: 1) the basis of host selection and 2) the occurrence of periodic outbreaks. Additional observational and experimental tests are necessary to test its validity.

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Abstract

Plant chemistry alone fails to explain why
some trees escape defoliation most of the time.
Chemical variation in space and time, acting to
enhance the effectiveness of natural enemies, may
be the key. Changes and increasing variation in
insect response to insect attack ("induction")
may be particularly important for irruptive pests.

Introduction

The search for an explanation for pest
outbreaks and cycles has long been a focus of
ecology and represents a multimillion dollar
question. It is interesting to consider, however,
that such outbreaks are actually rare. Few
insect species exhibit them, and they are widely
scattered in time (Schultz 1983a). Most insect
species do not exhibit irruptive population
dynamics, and exist at very low abundances almost
all the time (Lawton and McNeil 1979). The
occurrence of irruptions leads one to suspect
that some regulatory factor has failed or been
weakened. Since many things kill herbivorous
insects and/or influence their feeding, growth,
and fecundity, there is no shortage of possible
explanations. Nonetheless, no successful
generalization has emerged about these events;
instead, individual investigators favor
individual hypotheses (Schultz 1983a).

In our laboratory we emphasize the
influence of host tree quality, especially
defensive chemistry, on the performance of
defoliating insects. The reason for this is that
among those factors likely to be important to the
insect, food quality is one which may influence
others, including the effectiveness of
parasites, pathogens, and predators (Lawton and
McNeil 1979, Schultz 1983a). Our major working
hypothesis has two main parts: 1) tree chemistry
has an impact on defoliating insects, but
chemical variability is the key, and 2) the
importance of host chemistry derives from its
interaction with other mortality and morbidity
factors.

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The reason for following this line of
reasoning involves the observation that the
relationship between insect and host plant is
coevolutionary in nature (Ehrlich and Raven
1965). Each participant exerts natural
selection on the other, resulting in an escalating
"arms race". On the plant's part, chemicals may
be produced which function as defenses against
insects (Ehrlich and Raven 1965, Feeny 1970,
Swain 1979). However, the presence of these
chemicals selects for the ability to detoxify or
avoid them on the part of the insect (e.g.
Brattston 1979). If any plant or plant species
were to defend itself with a uniform, singular
chemical defense effective enough to keep
insects as rare as they are most of the time, we
would expect this strong selection to favor the
evolution of insects immune to it (Maiorana 1981,
Schultz 1983a). Exactly this result is common in
agricultural systems, where humans apply the
defense as artificial (or plant-derived)
chemicals, or employ uniform, resistant cultivars
(Lupton 1977). Since forest trees live many
years (and many insect generations), something
else must be important in defending them, because
"super pests" do not continuously defoliate
forests. We argue that "something else"
necessarily involves variable plant chemistry.

Induced Variability

A form of variation we have been studying
lately involves damage-induced changes in leaf
chemistry in forest trees. A decrease in food
value or increase in the concentrations of
antiherbivore chemicals has now been observed in
black oak (Wallner and Walton 1979), red oak
(Schultz and Baldwin 1982), red alder and willows
(Rhoades 1982), arctic birches (Haukioja and
Niemela 1978, Bryant 1981), yellow birch, sugar
maple, and poplars (Baldwin and Schultz 1983 and
unpublished), to mention a few. It is becoming
clear that tree leaf quality varies not only in
space (e.g., Schultz et al. 1981, Whitham 1981,
Zucker 1982) and seasonally (Feeny 1970, Schultz
et al. 1981), but also rapidly in response to
attack. We have found, for example, that
phenolic concentrations are increased as much as
150% in undamaged leaves of partially (10%)
defoliated sugar maples and poplars within 36
hours, apparently through *de novo* synthesis
(Baldwin and Schultz 1983).

The potential significance of this form of
leaf quality variability for understanding pest
outbreaks takes several forms. First, the ongoing
decline in food quality that results may help
explain the conspicuous decline in insect
population "quality" which occurs during
irruptive episodes, including slowed caterpillar
growth, reduced maximum size, and lowered
fecundity (Wellington 1965, Wallner and Walton
1979, Rhoades 1979, Schultz and Baldwin 1982).
Such declines often occur before available food
is depleted, suggesting possible food quality
reduction. Low food quality under induction
alternating with high food quality under
"relaxation" (and especially during periods of

plant stress) might generate the cyclic behavior some pest populations exhibit (Haukioja and Hakala 1975, Bryant 1981).

Second, increased effectiveness of predators, pathogens, and parasites as irruptions proceed could be due to or augmented by declining host plant quality (Schultz 1982). An estimated 26% increase in gypsy moth mortality due to tachinid fly infestation could result from the 3-4% reduction in caterpillar growth rates on "induced" foliage (Schultz 1983a). If lowered food quality influences searching behavior by larvae, so that more movement and tasting occur, contact rates with pathogens should increase (Schultz 1983a,b). Preliminary results in our laboratory suggest that gypsy moth larvae fed protein-deficient diets do indeed exhibit increased movement and searching behavior (Schultz, unpub. data).

A third potential consequence of the induction effect involves the role of spatial variability. More detailed chemical comparisons of oak leaves taken from trees being defoliated by gypsy moth larvae with those from unattacked trees growing nearby (see Schultz and Baldwin 1982 for sampling, extraction, and site descriptions) reveal differences in variability as well as total amounts of some phenolic compounds. Using capillary GLC methods for the quantitative analysis of two hydrolyzable tannins, gallic acid and ellagic acid (Arpino et al. 1977, Baldwin in prep.), we may plot the frequency distributions of leaves having various dry weight concentrations of these two astringent compounds. When we do this (Fig. 1), we find that undamaged leaves on "induced" trees exhibit significantly different frequency distributions (χ^2 test, $p < .05$). Leaves from damaged trees have a significantly wider range of values than do leaves from unattacked trees.

Any insect which can perceive these chemical differences has a wider range of leaf values from which to select a preferred type. In an induced tree, fewer leaves fall into the lower hydrolyzable tannin content classes; hence an insect responding to gallic and ellagic acids as antifeedants must search farther and longer for suitable leaves. This could increase metabolic travelling costs, search time per consumption time, contact rates with pathogens and predators, and conspicuousness to predators and parasites (Schultz 1983a,b). Increased variability, together with overall lower leaf quality, should increase a variety of risks.

Some insects may not discriminate among leaves, but eat the broader range found in induced trees. Recent evidence suggests that switching from high to low quality or low to high quality leaves can result in even poorer growth performance than is attained on a diet consisting of only poor quality leaves (E. Haukioja, unpub. data). In either case, induced trees which also exhibit increased variance could become much poorer hosts than they were before they were attacked.

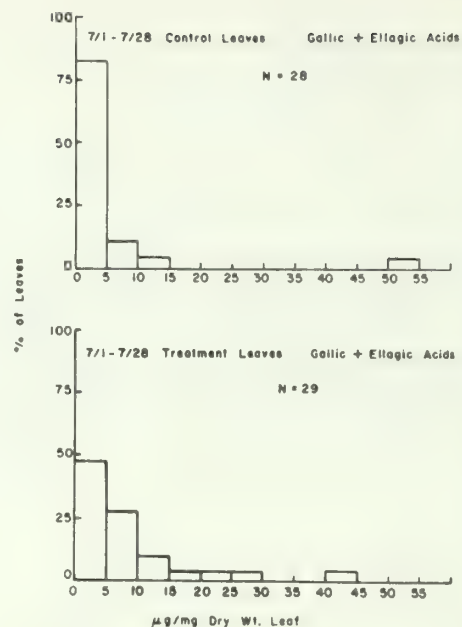


Figure 1. Frequency distributions of hydrolyzable tannin contents of leaves from red oak trees undamaged by gypsy moth larvae (top) and undamaged leaves from nearby trees defoliated 80-100% (bottom) during 1981.

Because the secondary chemistry of forest trees is often dominated by phenolics, especially tannins (Swain 1979), these are the compounds most studied in the context of induction. Recently, the importance of their biological activity as antiherbivore devices has been called into question (e.g., Bernays 1978, Martin and Martin 1983). Several investigators have found weak or nonexistent correlations between tannin contents and insect performance (e.g., Mattson, this volume, Wagner, this volume). There are at least two possible reasons for this. First, sampling for phenolics is made very difficult by the observation that tissue-to-tissue, leaf-to-leaf, and needle-to-needle variation is so great (Schultz et al. 1981). This means that we must know the phenolic/tannin content of the tissue actually consumed; it is not sufficient to sample similar, or even nearby tissues for correlative studies. The adjacent leaf may not represent or even resemble the chemical composition of the leaf an insect consumed. Second, both sampling and consumption can alter tissue chemistry. Hence, we have a catch-22: we must know what the chemical composition of a plant tissue was when the insect began to feed on it, but once the insect feeds on it, any remaining portion may be altered. In nature, insects may select low-phenolic tissues, but once partially eaten, our sampling and analysis may show them to be high-phenolic tissues.

Conclusions

This last point brings us to a point which is critical for understanding the role of tissue chemistry in the interaction between tree and insect. This observation is simply that because tissues vary tremendously in space and time, insects have a choice in selecting food. They may avoid tissues with one type of composition while seeking out tissues with other compositions, to which the insect may be physiologically adapted. As a result, understanding insect behavior and its sensory and ecological bases is central to explaining why certain insects eat certain tree species, move among individual trees, grow and reproduce better on some trees than others or at some times than others, or are more susceptible to natural enemies at certain times or in certain places. These issues, of course, are fundamental to answering the questions about population dynamics that interest us all. It is clear that studies of insect behavior, tree quality and tree chemistry are needed to understand insect population dynamics, but that we must pay as much attention to variances as to mean values.

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EFFECT OF FERTILIZATION ON WESTERN SPRUCE BUDWORM

FEEDING IN YOUNG WESTERN LARCH STANDS

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This study evaluated effects of fertilization of young western larch stands on western spruce budworm feeding in Montana. Various combinations of nitrogen, phosphorus, and potassium resulted in nearly double the amount of feeding by western spruce budworm larvae, with nitrogen eliciting the most response. Larch growth response to fertilization can be negated by increases in budworm feeding.

Introduction

Forest fertilization is relatively new to the Northern Rockies and is primarily limited to experimental areas. Western spruce budworm (*Choristoneura occidentalis* Freeman), a defoliating insect native to the Northern Rockies, has persisted in epidemic proportions since the late 1940's. Although reported long before that, it has not been considered a serious threat to forest management until about 1950. In the early 60's, it was discovered and described the feeding behavior of western spruce budworm on young western larch (*Larix occidentalis* Nutt.) (Fellin and Schmidt 1967). Instead of foliage feeding only, budworm were found feeding on and severing the stems of new shoots of larch, jeopardizing the straight form and rapid juvenile height growth characteristic of this species. Subsequent evaluations of this unusual feeding habit showed that indeed height growth was reduced about 25 to 30 percent by these terminal and upper lateral stem severances and that there was at least a temporary reduction in form quality (Schmidt and Fellin 1973; Fellin and Schmidt 1973a).

Silvicultural attempts at dealing with forest pest problems have a long history, particularly with some of the beetles. One of these cultural methods--fertilization--has had only limited evaluation. In a review, Mustanoja and Leaf (1965) noted that "fertilizers have differential effects on insects, the effects being more or less similar within certain genetic groups." They note, however, that "the populations and attacks of all studied species of macrolepidoptera . . .," of which they list four, ". . . have been reduced with mineral fertilizers (especially N) and lime." They attribute the effect to increased larval

mortality. In another review, Stark (1965) lists 28 fertilizer trials involving about a dozen species of forest insects in as many genera. In 21 of these trials, the treatment adversely affected the insects--including sawflies, shoot moths, aphids, and caterpillars--as reflected in reduction of cocoon or pupal density, increased larval mortality, decrease in female weight, and so forth. Six of the 28 trials showed no fertilizer effect and one showed increase in insect feeding.

In some specific examples, Merker (1958, 1961, 1963), studying 20- to 50-year-old spruce infested with *Pristiphora abietina*, found that he could significantly reduce pupal density and injury to shoots, sometimes in the same season, by applying NH_4NO_3 , CaCO_3 , or urea. Also, nitrogen applied as part of an NPK treatment to eastern white pine resulted in the least amount of damage by the white pine weevil, *Pissodes strobi* Peck, but the nitrogen treatment also resulted in the shortest trees (Xydias and Leaf 1964).

Conversely, there are documented cases where fertilizer increased the number of insects and/or stimulated feeding. For example, Xydias and Leaf (1964) found the greatest incidence of attack by the white pine weevil occurred with the same treatment of potash that resulted in the tallest trees. The treatment apparently made trees more palatable to the weevil. Also, Carrow (1967) found that the establishment rate of balsam woolly aphids (*Adelges picea* [Ratz.]) on Pacific silver fir (*Abies amabilis* [Dougl.] Forbes) grown on a humic, nitrogen-rich soil was 2.5 times as high as on host trees grown on a mineral nitrogen-poor soil. Increased pupal weights of spruce budworm (*Choristoneura fumiferana* Clem.) were found on nitrogen fertilized balsam fir (*Abies balsamea* [L.] Mill.). These increased pupal weights were in turn positively correlated with increased numbers of larvae produced per female moth (Shaw and others 1978). Hughes and Jackson (1962) found fertilizer mixtures of either N, P_2O_5 , or K_2O at the 100-lb/acre (112-k/ha) rate resulted in a highly significant increase in the incidence of attacks by a phloem insect, *Dioryctria amatella* (Hulst), to slash pine (*Pinus elliottii* Engelm. var. *elliottii*). Of the three components, incidence of attack was most closely associated with mixtures containing phosphorus. Even at the 50-lb/acre (56-k/ha) rate, phosphate in mixed fertilizers increased insect attacks fourfold over treatments containing no phosphate.

Soil type and/or host tree condition may be influential in the effect of some fertilizers on forest insects. In Sweden, poorly growing pine trees treated with phosphorus or nitrogen were little affected by attacks of the European pine shoot moth (*Rhyacionia buoliana* [Schiff.]). However, healthier trees treated with fertilizers affording phosphorus or nitrogen suffered heavy damage by the shoot moth (Eidmann and Ingestad 1963). Hughes and Jackson (1962) found *Dioryctria amatella* (Hulst) injury to slash pine most prevalent among fast growing trees; damage was negligible among slow growing trees of the same size in an adjoining plantation.

Insect predator-host relationships may also be involved in fertilizer responses. Thalenhorst (1964) warns against premature assumptions about the effects of fertilizers on insects. He describes a fertilizer trial in a spruce plantation where aphid species, mostly *Cinaropsis pilicornis*, infestations in May were heaviest on NPK and slightest on PK plots. However, since predator populations, particularly a lady beetle, *Coccinella septempunctata*, were also most numerous on these densely populated plots, the position was completely reversed a month later.

No general agreement exists on the mode of action in fertilizer interactions with insects. The physiology of the tree may be involved. Mustanoja and Leaf (1965) note that with some insects the sugar:protein ratio of the needles is important for nutrition of the larvae, and anything that decreases this ratio--water or mineral fertilizers, especially nitrogen--increases larval mortality. Carrow (1967) noted that an amino acid imbalance in the bark tissue of host trees was induced by fertilization with NH_4NO_3 and may have been responsible for a population decline of aphids. Also, nutrients may produce structural changes in host plant tissues that affect insect feeding. Lignification of plant tissues (Mustanoja and Leaf 1965), size of food (finely comminuted versus whole needles) (Merker 1961), and coarser bud scales or greater resin flow (Oldiges 1959) are all cited as possible effects of nutrient fertilization that in turn affected the feeding behavior of insects on the host trees.

Another hypothesis is that fertilizer elements are incorporated directly into various insect tissues, often with fatal or deleterious effects. Merker (1962) notes that the direct effects of absorbed fertilizers on forest pests are much more severe than any indirect effect upon the physiological condition of the tree. However, Carrow and Graham (1968) imply that treatment of host trees with ammonium nitrate reduces populations of the balsam woolly aphid primarily by inhibiting initial settling of larvae on the host trees.

Although there is apparently little consistency in the results of fertilizer trials--due in part at least to questionable observations on

small plots, lack of knowledge of the nutritional and moisture relations of the soils, or impracticable methods--there does appear to be general agreement that fertilization affects the behavior of many insect populations (Stark 1965).

Neither the technical or economic aspects of forest fertilization are well understood, particularly in the Northern Rockies. Nevertheless, it is important that tree response to fertilization and interactions with other factors in the ecosystem be evaluated. With this in mind, we undertook the subject of this paper--the interaction of western spruce budworm with different combinations of fertilizers in young western larch forests of western Montana. This is the first report of the results of this exploratory study.

Methods

This western spruce budworm study was superimposed on a conventional fertilizer study that aimed primarily at determining the effect of different combinations of fertilizer on growth of young western larch forests. The original fertilizer/growth study established in 1966 consisted of 175 experimental plots at 13 locations in western Montana (Behan 1968). The basic design of the original fertilizer/growth study was a randomized block of six treatments replicated three times at each location. However, because of limited area or lack of sufficient homogeneity of the stands, it was not always possible to apply all six treatments. Hence, at each location, there were from two to six treatments, including controls of no fertilizer, but always three replications.

The fertilizer/budworm study reported here was established 2 years later in 1968 and was limited to four of the 13 locations of the original fertilizer/growth study. All four locations were within the budworm-infested areas of the Lolo and Flathead National Forests. The treatment combinations on these four plots are shown in Table 1, where the control had no fertilizer and the treatments were composed of various combinations of nitrogen, phosphorous, and potassium.

Table 1. Description of site, stand, and treatments used for this larch fertilizer/western spruce budworm study.

Location	Age	Stand condition at time of treatment		Site index (50 yr)	Treatments
		Height (feet)	Average density (trees/acre)		
Upper Cottonwood	12	6 to 12	7,000	60	Control, NPK
Lower Cottonwood	12	4 to 8	300 ^{a/}	65	Control, NPK, NK, NP, PK
Rice Ridge	18	5 to 15	3,500	70	Control, NPK, NK, NP, PK
Barber Creek	11	4 to 10	3,600	80	Control, NPK, PK

^{a/} thinned.

Nitrogen (N) was in the form of urea at the rate of 300 lb/acre (336 k/ha), phosphorus (P) was treble superphosphate at the rate of 200 lb/acre (224 k/ha) of P_2O_5 (phosphorus pentoxide), and potassium (K) was potassium chloride at the equivalent of 200 lb/acre (224 k/ha) of K_2O (potassium oxide). For example, the NPK treatment consisted of 300 lb nitrogen, 200 lb phosphorus, and 200 lb potassium per acre. Fertilizers were preweighed and applied separately with a hand spreader on the plots.

To sample the interaction of the budworm and the fertilizer treatments, five of the tallest trees per plot were randomly selected. Each tree was stratified vertically into six strata. In each stratum, beginning with the topmost stratum, we selected a branch or branches and examined the first 100 fascicles, beginning distally on the branch. Branches selected were in a helical pattern moving down the tree; i.e., the first branch selected on the south side of the tree, the next on the southwest, the next on the west, and so forth. Each branch was tagged for initial and subsequent measurements. On these 100 fascicles, we determined the number of larvae and the number of fascicles damaged during the larval feeding period. After the larval feeding was completed, we examined the same 100 fascicles to determine the number of damaged fascicles. Larvae counts were made the second year after fertilization on all four study areas. Observations, but no larval counts, were made in measurement years four and six.

In addition, on these same branches in each stratum, we determined the larval damage done to the lateral shoots in four categories: (a) no feeding; (b) needle feeding only; (c) external mining of the shoot; and (d) shoot severed (fig. 1). Damage to the terminal shoot of each tree was evaluated and classified into the same four damage categories listed for the lateral shoots.

Measurements of injuries caused by western spruce budworm larvae were taken in 1968, 1970, and 1972--2, 4, and 6 years after the fertilizers were applied in fall of 1966.

Results

Western spruce budworm larvae fed on the young western larch trees on these fertilizer study plots in much the same manner we described earlier (Fellin and Schmidt 1967, 1973a; Schmidt and Fellin 1973). However, budworm fed more heavily on larch in the fertilized plots than they did in the control plots. Overall, the effects of fertilizer treatment on budworm feeding were essentially the same on all four study areas. The absolute amount of budworm damage varied by area because of difference in budworm populations, but the ratios of larval damage in the fertilized and control plots were much the same. The following sections describe the types and amounts of budworm feeding as related to fertilizer treatment.

Fascicle Damage

The first noticeable budworm damage to larch in the spring was from larvae feeding on the larch fascicles. Fascicle needles started emerging in late March, well before the terminal and lateral shoots started to elongate (Schmidt and Lotan 1980). Thus, the fascicle needles were the first readily available source of foliage for the budworm on young larch.

Budworm fed on fascicles about one and a half to twice as much on the fertilized plots as they did on the control (not fertilized) plots (Table 2). This was particularly apparent on any of the plots where nitrogen was at least one of the components of the fertilizer treatment. Effects of PK treatment on budworm feeding were far less pronounced than those treatments that included nitrogen, but damage on the PK treatment exceeded that on the control plots.

Table 2. Percent fascicles injured by western spruce budworm larvae 2 years after fertilization.

Treatment	Lower	Upper	Rice	
	Cottonwood	Cottonwood	Ridge	Barber
	(percent)			
NP	25	--	28	--
N	28	--	23	3
NK	22	--	26	--
Control	12	6	13	2
PK	14	--	18	--
NPK	20	15	21	2

Larvae fed on fascicles throughout the crown but fed more heavily on those in upper strata of the live tree crowns (Fig. 2). The number of fascicles fed on was about three times heavier in the upper crown than in the lower crown. This is consistent with observations we had made earlier of budworm feeding behavior (Schmidt and Fellin 1973).

Lateral Shoot Damage

Budworm larvae severed about one and a half to twice as many of the succulent new shoots of lateral branches on fertilized plots as on the control plots (Table 3). Over half of the lateral shoots were severed by budworm larvae on the fertilizer plots at Rice Ridge the second year after fertilization compared to about one-fourth of the lateral shoots on the control trees. Like fascicle feeding, the PK treatment results fell intermediate between those treatments that included nitrogen and the control. Since the above injuries coincided with a generally heavy budworm infestation in the area, practically none of the trees escaped some type of budworm feeding, even those on the control plots. Only 8 percent of the trees in the control plots weren't fed on in some manner.



Figure 1a. Types of western spruce budworm feeding on western larch--no feeding.



Figure 1c. Types of western spruce budworm feeding on western larch--external mining of the shoot.



Figure 1b. Types of western spruce budworm feeding on western larch--needle feeding only.



Figure 1d. Types of western spruce budworm feeding on western larch--shoot severed.

FIGURE 2. NEEDLE FEEDING (PERCENT)

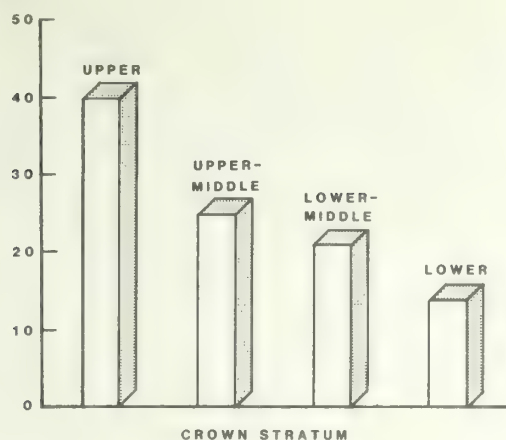


Figure 2. The percent of fascicles fed on by western spruce budworm larvae at four crown levels 2 years after fertilization (Lower Cottonwood). This includes only the upper four of the six crown strata. The lower two strata were in the receding portion of this shade-intolerant species and showed practically no budworm feeding.

Table 3. Percent lateral shoots of western larch severed by western spruce budworm at Rice Ridge and Lower Cottonwood 2 years after fertilization.

Treatment	Type of damage			
	Rice Ridge		Lower Cottonwood	
	None	Lateral shoots severed	None	Lateral shoots severed
	-- (percent) --			
NP	1	56	10	65
N	1	53	6	68
NK	1	52	5	65
Control	8	23	21	34
PK	2	44	25	37
NPK	1	54	10	58

We see little difference in percent lateral shoots severed between those four treatments that included nitrogen (Fig. 3). Budworm severed about twice as many of the lateral shoots on the nitrogen treated plots as on the controls. Lateral shoot severance ratios on the PK treated plots were intermediate to the controls and the plots with nitrogen.

The effect of fertilization on lateral shoot severance by western spruce budworm larvae was relatively consistent from area to area. The absolute amount of damage varied by area because of differences in budworm populations, but the ratios of damage on the NPK and control plots were much the same (Table 4). Lateral shoot severances were about one and a half to twice as great on NPK plots as on the controls.

RATIO STEM SEVERANCES (FERTILIZED/CONTROL)

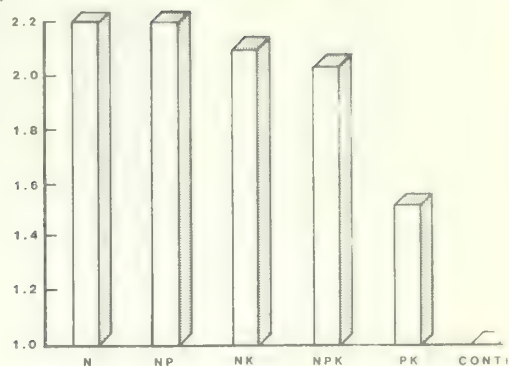


Figure 3. Budworm severance ratios on fertilized and control plots (fertilized/control) at Lower Cottonwood and Rice Ridge 2 years after fertilization.

Table 4. Effect of NPK fertilizer on the percent of lateral shoots severed by western spruce budworm larvae on four study areas two years after fertilization.

Damage	Area	Control	NPK ^{a/}
		--(percent)--	--
Shoots severed	Lower Cottonwood	36	54
	Upper Cottonwood	34	58
	Rice Ridge	39	67
	Barber	7	10
None	Lower Cottonwood	21	10
	Upper Cottonwood	28	14
	Rice Ridge	1	1
	Barber	84	82

^{a/} The NPK and control treatments were the only treatments common to all four study areas.

The effect of budworm larval populations is most readily detected in the trees that had no damage (Table 4). For example, Rice Ridge had a high budworm population 2 years after fertilization and only 1 percent of the lateral shoots escaped both needle feeding and severance in both the NPK and control plots. Meanwhile, on the Barber area where budworm populations were light, over 80 percent escaped all types of damage.

Fertilization effects on budworm feeding, particularly in the most severe form of feeding (shoot severance), diminished rapidly (Table 5). The largest absolute differences in budworm feeding by fertilizer treatments occurred the second year after fertilization. This coincided with the year of greatest tree diameter growth response to fertilization (personal communication with Dr. Mark Behan, University of Montana, Missoula, 1982). Evaluations to determine treatment effects the fourth year after fertilization were confounded by a dramatic reduction in budworm

Table 5. Effect of NPK fertilizer on budworm shoot severances 2, 4, and 6 years after fertilization on four study areas.

Damage	Years since fertilization	Control	NPK
		(percent)	
Shoots severed	2	25	41
	4	8	8
	6	29	32
None	2	29	22
	4	83	84
	6	37	31

populations throughout much of western Montana in 1969, the third season after fertilization. An unseasonal cold-wet spell in June of that year reduced budworm populations about 90 percent and budworm injuries up to 70 percent the following season (Fellin and Schmidt 1973b). However, western spruce budworm populations resurged rapidly following their decimation by the frost--the number of shoots severed in the control plots in year 6 were back to, and had actually exceeded, what they were in year 2 (Table 5).

The data hint that there were small residual effects of fertilization on budworm feeding in year 6--the percent of lateral severances was slightly greater on the NPK treatment and also fewer totally undamaged trees than on the control.

Terminal Shoot Damage

Budworm feeding on terminal shoots was essentially the same as that on the lateral shoots and fascicles--damage was highest on the fertilizer treatments that included nitrogen, intermediate on the PK treatment, and lowest on the control plots (Table 6). Larvae severed about one and a half to twice as many of the terminal shoots on the fertilized plots as on the controls.

Table 6. Percent of terminal shoots severed by larvae 2 years after fertilization.

Treatment	Area	
	Lower Cottonwood	Rice Ridge
	(percent)	
NP	53	87
N	60	67
NK	53	67
Control	33	47
PK	40	73
NPK	60	67

We consider the severance of terminal shoots the most severe damage that budworm inflicts on western larch because it reduces both the rapid height growth and excellent bole form of western larch--two very desirable attributes of larch (Schmidt and Fellin 1973)(Fig. 4).

The incidence of damage was higher on the terminal shoots than on any other portions of the tree, a relationship that supports results of some of our earlier studies (Fellin and Schmidt 1973a; Schmidt and Fellin 1973). For example, at Rice Ridge, where budworm populations were high 2 years after fertilization, over three-fourths of the terminal shoots were severed on the fertilized plots compared to only about half of the lateral shoots.

Budworm Feeding Relationships

Certainly, fertilization did not deter any larval feeding on larch. Rather, all types of feeding were enhanced by fertilization, but the increases of the fertilized plots over that of the controls were least in needle feeding and greatest in the more severe form of feeding--the shoot mining and severances (Table 7). Using Lower Cottonwood as the example and a ratio of NPK/Control, the apparent increase in needle feeding due to NPK had a ratio of only about 1.14 2 years after fertilization. At the same time, the ratio for lateral shoot mining was 1.78 and that for lateral shoot severance was 1.71.

Table 7. Effect of NPK fertilizer on type of budworm feeding, 2, 4, and 6 years after fertilization at Lower Cottonwood.

Damage	Control			NPK		
	Year			Year		
	2	4	6	2	4	6
	(percent)					
None	21	84	28	10	84	2
Needle feeding	79	16	72	90	16	7
Lateral shoots mined	37	5	38	66	7	4
Lateral shoots severed	34	4	35	58	5	4

Consistent with earlier studies (Schmidt and Fellin 1973), about 90 percent of those shoots mined were also severed--the budworm nearly always succeeded in severing the shoots.

Larval feeding damaged fascicles early in the season and was directly related to the number of lateral shoots severed later in the season (Fig. 5). There was a strong linear relationship of fascicle feeding to lateral shoot severances when data from all areas and years on both the NPK and control plots were combined. For example, if about 20 percent of the fascicles were fed on, about 50 percent of the lateral shoots could be expected to be severed a little later. There was no detectable difference in this relationship between the fertilized and control plots.



Figure 4a. Effects of western spruce budworm feeding on the form of the upper bole of western larch--no budworm feeding.



Figure 4b. Effects of western spruce budworm feeding on the form of the upper bole of western larch--repeated budworm feeding.

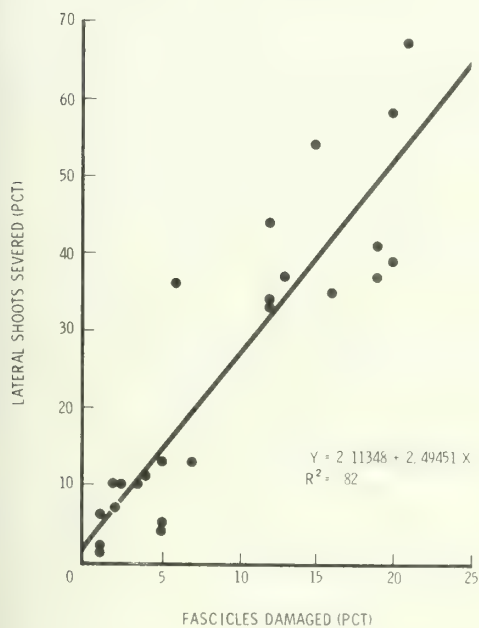


Figure 5. Relationship of the percent of fascicles fed on and the percent of lateral shoots severed by western spruce budworm larvae.

Conclusions

Fertilization is still in its infancy in forests of the Northern Rockies, but as management intensifies, it may become a practical forest management tool. Like many management practices, the introduction of fertilizers into a natural ecosystem can be expected to affect elements of the system other than that to which the practice is directed. In this study, the objective of the fertilization treatment was to accelerate tree growth, but we discovered that the fertilizers also influenced the feeding behavior of western spruce budworm larvae. Our evaluation for the first 6 years after fertilization showed that:

1. Fertilization increased all types of budworm feeding on young western larch, including fascicle feeding, needle feeding on the lateral shoots, lateral shoot mining, and severances of lateral and terminal shoots.
2. All fertilizer combinations tested resulted in increases in budworm feeding.

included nitrogen increased the incidence of budworm feeding the most with an intermediate effect shown by the fertilizer that had no nitrogen (PK).

4. Fertilizers that included nitrogen increased the incidence of budworm feeding in the general range of one and a half to twice that found on the control plots.
5. Fertilizer effects on budworm-feeding appeared relatively short-lived, with the effects most pronounced the second year after treatment and declining rapidly after that.
6. Practically none of the trees, even on the control plots, escaped some type of budworm feeding the second year after fertilization, a year that coincided with a generally heavy budworm infestation.
7. Budworm feeding was most pronounced in the upper crowns of both fertilized and nonfertilized trees with no apparent changes in this feeding pattern due to fertilization.
8. The effects of fertilization on budworm feeding, in relation to the controls, were relatively consistent from area to area, in spite of differences in budworm populations on the different areas.
9. The most severe forms of budworm feeding--shoot severances--were increased the most by fertilization.
10. Damage to the terminal shoots was the most pronounced of any of the damage categories, and from determinations we made from earlier studies, can be expected to have the most pronounced effect on tree development.

Why these fertilizer treatments affected the feeding behavior of western spruce budworm larvae is not explained by this study. Our study areas were relatively small and our sampling indicated that larvae were evenly distributed. Therefore, the condition of the tree--the feeding substrate for the budworm--must be the major factor affecting the budworm larvae response to the fertilizers. We postulate that at least two factors may help explain this feeding response: (1) The nutritional status of needle and shoot components of fertilized larch trees are improved by fertilization. This more favorable diet may result in more vigorous and active budworm larvae capable of increased feeding activity. (2) Budworm larvae find the fertilized trees a more favorable substrate and fewer of them disperse from the tree to the forest floor where they succumb to unfavorable physical and biological conditions.

Nutritional studies may help explain why some of these interactions between budworm larvae and fertilized trees occur. In the meantime, it appears that fertilization of larch stands within areas of heavy budworm infestation should be delayed until budworm populations decline. During

fertilization on larch tree growth and vigor can be largely negated by increased budworm feeding.

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BUDWORM FECUNDITY AND FOLIAR CHEMISTRY: INFLUENCE OF SITE

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ABSTRACT

Two Maine spruce-fir stands having different budworm populations were sampled to determine the relationship between spruce budworm weight (fecundity) and foliage quality. Although much of the variation in budworm weight was attributable to other factors, significant correlations between budworm weight and multiple foliar nutrient concentration variables suggest that foliage quality altering silvicultural practices such as fertilization may manipulate populations of the spruce budworm.

Introduction

One of the many questions that needs to be answered concerning the relationship between the spruce budworm (*Choristoneura fumiferana* Clem.) and the spruce-fir forest concerns the hypothesis that site productivity influences the susceptibility of these valuable forests to spruce budworm outbreaks. Quantification of this theoretical relationship is a highly desirable goal because this information could be used to develop a hazard rating scheme based on differential site productivity. This would facilitate decision making by forest managers or pest management specialists who must determine how and where to allocate limited time and financial resources.

In addition to the obvious variation in productivity associated with sites that have vastly

different gross characteristics, it is also important to consider the more subtle variation in site productivity that may be expressed in differential foliar nutrient concentrations (Czapowskyj, 1979; Tilton, 1978). The latter is intuitively appealing because evidence suggests that nutritional, structural, and allelochemical quality of foliage consumed by budworm (Mattson and Koller, in press) may significantly alter important behavioral and population characteristics such as propensity to feed (Albert et al., 1982), survival of larvae, fecundity (Shaw et al., 1978), and oviposition (Stadler, 1974).

Forest fertilization is a means by which wood and fiber production can be increased in the spruce-fir forest. Fertilization, however, significantly alters foliar nutrient concentrations (Czapowskyj et al., 1980; Briggs et al., 1981). Inclusion of foliar nutrient information in an equation that defines the relationship between site productivity and the intensity and duration of budworm infestation would allow researchers to evaluate forest fertilization not only in the context of its primary goal of increased production, but also its impact on the spruce budworm. For example, Xydias and Leaf (1964) indicated that fertilization increased damage to white pine (*Pinus strobus* L.) by the white pine weevil (*Pissodes strobi* Peck), negating beneficial effect of this management option on tree growth and bole quality. A number of other studies have demonstrated the impact of forest fertilization and tree nutrition on insect and disease organisms (e.g., Baule, 1973; Campbell, 1976; Carrow and Graham, 1968; Cooke et al., 1978; Mitchell and Paul, 1974; Moore and Layman, 1978; Mustanoja and Leaf, 1965; Roberts and Chow, 1977; Smirnoff and Bernier, 1973; Weiner and Mirkes, 1972; White and Leaf, 1957).

The objective of our study in Maine was to quantify the relationship between selected physical characteristics of the spruce budworm and site productivity in mixed stands of red and white spruce (*Picea rubens* Sars.; *Picea glauca* (Moench) Voss.) and balsam fir (*Abies balsamea* (L.) Mill.) growing on two sites that differed in soil type and drainage. It is anticipated that the results of this and similar studies will contribute toward (1) the development of diagnostic criteria to evaluate the susceptibility of forest stands to budworm outbreaks based on analyses of host or site conditions and (2) elucidation of the consequences of inadvertently stimulating an increase in spruce budworm populations when spruce-fir stands are commercially fertilized.

Methods

Site Descriptions

Two study areas were selected during the 1980 field season as suitable for this investigation. The first, designated as the dry site, is located in Little Squaw Township, Piscataquis County, Maine, and is occupied by a 50-70 year-old stand consisting primarily of balsam fir and red spruce with lesser quantities of American beech (*Fagus grandifolia* Ehrh.) and yellow birch (*Betula*

alleghaniensis Britton). Stand basal area is approximately 230 square feet/acre at a density of about 470 trees/acre, with an associated site index of 53 for red spruce and 58 for balsam fir. Understory vegetation is limited to seedlings of the overstory species in addition to a number of herbaceous species. The soils belong to the Chesuncook catena and consist of a complex of the Telos and Chesuncook series. These soils were developed in glacial till derived from slates, phyllites, and a mixture of other dark and low grade metamorphic rocks. The Telos soil is a deep, somewhat poorly drained soil with a seasonal high water table depth of about eight inches. Internal drainage is moderate through the solum of this soil, with much of the water moving laterally across the surface of very compact glacial basal till that occurs at a depth of about 16 inches, which marks the depth of maximum root penetration. The deeper Chesuncook soil has a seasonal high water table depth of about 16 inches and exhibits tree root penetration to a depth of 18 inches. A compact layer of basal glacial till occurs at a 20 inch depth. Both the Telos and Chesuncook soils are classified as coarse-loamy, mixed, frigid, Aquic Dystrochrepts.

The second area, designated as the wet site, is located in Thorndike Township, Somerset County, Maine, and is occupied by a stand of similar age and composition to that on the dry site except for the presence of sugar maple (*Acer saccharum* Marsh.) and northern white cedar (*Thuja occidentalis* L.). Stand basal area is approximately 205 square feet/acre at a density of 55 trees/acre, with an associated site index of 48 for red spruce and 49 for balsam fir. The soils also belong to the Chesuncook catena but are members of the Monarda series of coarse-loamy, mixed, frigid, Aeric Haplaquepts. On this soil, root growth is restricted to an organic mat and an underlying cobble and gravel zone 2-6 inches thick. Although the seasonal water table depth varies with local precipitation, the root zone in this soil may not drain until several days after precipitation events (Schiltz and Grisi, 1980).

Budworm/Foliage Sampling and Analysis

A total of 38 randomly selected dominant and codominant balsam fir and red spruce trees with relatively full crowns and no evidence of excessive budworm feedings or other damage were chosen for analysis. Late stage larvae (sixth instar) and pupae were collected during the period of June 30-July 15, 1980, from 45 cm long midcrown branch tips taken from the midcrown of each of the sample trees using a pole pruner with basket attachment. When the population density permitted, enough healthy insects were collected to insure that 20 female moths would be obtained from each sample tree. The pupae were weighed the day of collection or within 24 hours of formation and placed in separate cups until moth emergence, at which time moths were weighed within eight hours of eclosion, frozen, oven-dried at 60°C to constant weight, and reweighed.

Current (1980), one year (1979), and two year-old (1978) foliage for element analysis was

collected in late August and early September from the upper third of the crown. Foliage analyzed for organic materials was obtained in early July from the same midcrown branches used for samples of late stage larvae. All foliage was put on ice in the field, and transferred to freezers the day of collection. Foliage for element analyses was oven-dried at 60°C to constant weight and ground in Wiley Mill equipped with stainless steel fitting to a size that permitted passage through a 100 micron sieve. Subsample foliar N concentration was determined using the macro-Kjeldahl method (Wiley et al., 1972). Additional foliar subsamples were dry-ashed (Parrow, 1976) and analyzed for P using the ammonium-molybdate-vanadate method (Jackson, 1958) and K, Ca, and Mg using atomic absorption spectrophotometry.

For organic analyses, freeze-dried foliage was ground to pass through a 100 micron sieve. A 70% subsample was mixed with 3 ml of methanol:chloroform:water (12:5:3), placed in an ultrasonic bath for ten minutes, centrifuged, and the supernatant decanted. This extraction process was repeated twice. To the combined supernatant, 2 ml chloroform and 4 ml water were added followed by mixing and centrifugation. Top layer volume was recorded and aliquots taken for phenolic and sugar analyses.

Total phenols were determined with Folin-Denis reagent using procedures recommended by Rosenblatt and Peluso (1944) on a semi-micro scale. Specifically, a 25 to 100 microliter extract was diluted with water to 7 ml followed by the addition of 1 ml of Folin-Denis reagent and 0.6 ml of a saturated solution of sodium carbonate. The solution was read at 730 nm after 10 minutes against a reagent blank. Gallotannin was used as a reference standard.

Flavanol content, including dihydrochalcones and proanthocyanidin oligomers, was determined with freshly prepared 1% vanillin in 70% sulfuric acid reagent (Swain and Hillis, 1959). A 25 microliter extract was added to each of two test tubes containing 1 ml water in an ice bath. One tube received 2 ml of reagent and the other 2 ml sulfuric acid followed by mixing. The tubes were removed and read after 15 minutes against a blank of 25 microliters methanol, 2 ml reagent, and 1 ml water. Catechin served as a reference standard.

Condensed tannin content was estimated by forming anthocyanidins. This was accomplished by heating a 50 to 200 ml sample of extract in 5 ml 5% concentrated hydrochloric acid in 1-butanol for 1.5 hrs at 95°C. The sample was read at 548 nm against a reagent blank. Correction for interfering pigments prevalent in early season samples was made by placing the sample in acetic acid:ethanol, 1-butanol, (1:3:16). A purified condensed tannin from July red oak leaves served as a reference standard.

Sugars were analyzed by gas chromatography. A 4 ml aliquot of extract was dried under nitrogen and silylated sugar oximes formed using hexamethyldisilazane and hexamethyldisilazane pyridine (Pierce Handbook and General Catalog, 1979-80). Phenyl-Beta-glucopyranoside was added as an internal standard and commercially available

ent grade sugars serves as references. Chromatography was on a 2 m x 2 mm column of 3% OV-17 on a temperature program of 170 to 275°C at 10 min with detection by FID. Peak areas were integrated to mg/sample by the internal standard method.

Statistical Analyses

Using foliar nutrient concentration as measures of site productivity, Pearson correlations (Spearman and Cochran, 1967) were generated to relate average pupal wet weight, moth wet weight, moth dry weight to the N, P, K, Ca, Mg, fructose, glucose, sucrose, total free sugar, total phenol, flavanoid, and condensed tannin concentrations in the foliage from the different age classes on an individual tree basis across both sites and species. Additionally, general linear models were constructed to determine which factors accounted for a significant amount of the variation in the budworm variables. In addition to the foliar nutrient concentration values, dummy variables that defined the different study sites and years examined were tested for inclusion in the models (Freund and Littell, 1981).

Results and Discussion

The correlation coefficients between the budworm and foliar nutrient concentration variables are provided in Table 1. Both budworm variables were highly significantly correlated with foliar N concentrations in all foliage age classes. The strongest correlations occurred in current year foliage. Both budworm variables were highly significantly correlated with glucose, fructose, and total free sugar concentrations in current year foliage. These findings are consistent with the results of Harvey (1974, 1975),

Shaw and Little (1977), and others, who demonstrated that the spruce budworm develops better on foliage that contain sugars and nitrogenous compounds at higher levels. Both budworm variables were also significantly correlated with Mg, total phenol, and flavanoid concentrations in current year foliage, while pupal weight was significantly correlated with P, Ca, and condensed tannin levels in current year foliage and with K concentrations in two year-old foliage. In all cases the significant correlation coefficients were positive. While it was not surprising to find pupal weights positively correlated with nutrients and carbohydrates since these are required for growth, the positive correlation with phenolic and tannin levels was unexpected. These compounds supposedly function as digestion inhibitors by binding with protein (Feeney, 1969); hence, would be expected to be negatively correlated with weight gain.

The data indicate that foliage with higher nutrient concentrations is likely to foster development of spruce budworm pupae and moths with greater individual mass and, presumably, fecundity. This suggests that high foliar nutrient concentrations caused by inherent differences in site quality or the result of silvicultural practices such as fertilization may increase the fecundity of the spruce budworm to such an extent that the net effect of such practices may actually be a reduction in wood and fiber production.

The linear models containing the factors that account for a significant amount of the variation in the budworm variables are provided in Table 2. The model with pupal weight as the dependent variable produced an r-square value of 0.29, while the model with moth dry weight as dependent variables yielded a r-square of 0.69. In both models, the dummy variables specifying site and specific differences were statistically significant. The only

Table 1. Pearson correlation coefficients between pupal weight or adult dry weight and foliar chemistry.

	Pupal wet weight			Pupal dry weight		
	Foliage age			Foliage age		
	Two-year	One-year	Current	Two-year	One-year	Current
N	0.471***	0.520***	0.634***	0.460***	0.849***	0.583***
P	-0.094	-0.025	0.415	-0.248	-0.205	0.197
K	0.355**	0.191	-0.365	0.254	0.176	-0.144
Ca	-0.063	0.046	0.466***	-0.163	-0.050	0.308
Mg	-0.036	0.217	0.567***	-0.029	0.201	0.493***
Fructose	0.487	-----	0.688***	0.422	-----	0.621**
Glucose	-0.109	-----	0.750***	0.649**	-----	
Sucrose	0.139	-----	0.347	0.124	-----	0.263
Total free sugars	0.319	-----	0.731***	0.272	-----	0.706***
Total phenols	0.105	-----	0.634**	0.207	-----	0.483*
Flavanoids	-0.281	-----	0.614**	-0.183	-----	0.501*
Condensed tannins	0.438	-----	0.502*	0.551	-----	0.440

*, **, and *** indicate significance at the alpha = .10, .05, and .01 levels, respectively.

foliar nutrient concentration value that contributed a significant amount of information about the budworm variables after differences due to site and species were accounted for was the K level in current year foliage, which was included in the model where moth dry weight was the dependent variable. The significant relationship between budworm variables and concentrations of foliar chemicals (Table 1) are totally masked by the inclusion of dummy variables specifying site and species differences. However, these variables have likely achieved significance due to the significant differences in nutrient concentrations that exist between sites (Table 3) and species (Table 4).

Table 2. Significant sources of variation in pupal weight and moth dry weight including estimates of regression coefficients and means.

Dependent Variable: Pupal Weight (g) $r^2=0.29$					
Parameter	Estimate	Std. Error	T value	P	> T
Intercept	0.0499	0.0035	14.39	0.0001	
Site	0.0105*	0.0041	2.56	0.0159	
Species	0.0101#	0.0040	2.53	0.0172	

Table 2. continued

Dependent Variable: Moth Dry Weight (g) $r^2=0.69$

Parameter	Estimate	Std. Error	T value	P	> T
Intercept	0.0018	0.0039	0.45	0.65	
Site	0.0040*	0.0014	2.89	0.01	
Species	0.0084#	0.0018	4.71	0.00	
K levels in current year foliage					
	0.0111	0.0043	2.61	0.01	
Pupal Weight					
Adult Dry Weight					
Site	Mean	Std. Error	Mean	Std. Error	
Dry	0.066	0.003	0.018	0.001	
Wet	0.056	0.003	0.013	0.001	
Species					
Balsam Fir	0.064	0.003	0.020	0.001	
Red Spruce	0.054	0.003	0.013	0.001	

*Multiply by 1 if site = dry, 0 if site = wet.
#Multiply by 1 if species = balsam fir, 0 if species = red spruce.

Table 3. Mean concentrations (%) of foliar chemicals in current, one and two year-old foliage by site.

	Two year		One year		Current	
	Dry	Wet	Dry	Wet	Dry	Wet
N	1.133	1.022*	1.221	1.110*	1.260	1.156
P	0.082	0.105*	0.092	0.111*	0.120	0.139
K	0.486	0.504	0.556	0.597	0.737	0.910
Ca	0.612	1.280*	0.760	1.405*	0.572	0.605*
Mg	0.103	0.142*	0.149	0.188*	0.175	0.155
Fructose	1.704	1.349	1.383	1.928	1.866	1.256
Glucose	3.016	3.270	2.450	1.652	3.591	0.999*
Sucrose	0.627	0.674	0.058	0.118	0.401	0.056
Total free sugars	5.345	5.171	4.890	3.700	6.005	2.311*
Total phenols	8.050	8.375	6.290	4.300	4.228	3.068*
Flavanoids	6.950	8.668	5.550	3.050	3.905	2.263*
Condensed tannins	5.800	5.148	3.540	3.100	2.902	2.282

*Indicates statistical significance between site at the alpha = 0.05 level.

Table 4. Mean concentrations (%) of foliar chemicals in current, one and two year-old foliage by species.

	Two year		One year		Current	
	Fir	Spruce	Fir	Spruce	Fir	Spruce
N	1.261	0.870*	1.304	0.990*	1.420	1.119*
P	0.097	0.098	0.101	0.108	0.136	0.129
K	0.533	0.463	0.578	0.589	0.637	0.906*
Ca	1.467	0.611	1.775	0.605*	1.032	0.418*
Mg	0.147	0.111	0.226	0.125*	0.245	0.132*
Fructose	1.420	-----	1.383	1.928	2.030	1.479*
Glucose	3.219	-----	2.450	1.652	5.555	1.313*
Sucrose	0.665	-----	0.058	0.118	0.720	0.069*
Total free sugars	5.206	-----	4.890	3.700	8.307	3.001*
Total phenols	8.310	-----	6.290	4.300	6.014*	2.755*
Flavanoids	8.324	-----	5.550	3.050	5.320*	2.377*
Condensed tannins	5.278	-----	3.540	3.100	3.646*	2.219*

*Indicates statistical significance between species at the $\alpha = 0.05$ level.

Examination of respective site and species indicated that pupae and moths from the dry site were significantly heavier than those from the wet site, and pupae and moths from balsam fir were significantly heavier than those that were on red spruce. Although both site and species effects are significant, the differences attributable to species are greater than those due to site.

Conclusions

The results of this study support the hypothesis that size (fecundity) of the spruce budworm is, in part, related to site productivity measured by obvious physical differences in site and/or foliar nutrient concentrations. The budworm variables examined in this study were significantly correlated with a number of foliar nutrient concentration values. Dummy variables representing specified differences in sites and species were statistically significant for all budworm variables examined in general linear models designed to identify sources of variation in budworm characteristics.

However, r-square values for the linear models are not satisfying, in that a large proportion of the variation in the budworm variables cannot be accounted for by differences in site productivity as expressed by the variables selected. This, however, is not unexpected in view of the diverse extrinsic and intrinsic factors that may influence budworm fecundity (Miller, 1963).

Furthermore, similar relationships must be determined for a range of site conditions and budworm population histories to assure that the results obtained are representative of and applicable to a broader range of field conditions. This is especially important in view of interstand differences that may exist in regression models that describe fecundity as a function of budworm size (Miller, 1957). Numerous studies have demonstrated a relationship between insect fecundity and food quality. The question that must be addressed now concerns the biological significance of statistically significant results. For example, how many eggs are represented by a difference of 0.010 g in mean pupal weight? Is this difference enough to significantly alter the population dynamics of the budworm?

Although experimental results are not conclusive and are based on a limited number of samples, evidence suggests that those interested in improving spruce-fir forest productivity through fertilization will need to balance the opportunity to generate additional revenue from increased outputs of wood and fiber against the possibility that elevated foliar nutrient concentrations will stimulate destructive populations of the spruce budworm.

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ANALYSIS

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A differential equation model of gypsy moth abundance, average larval dry weight, and food abundance was used to analyze the effects of changes in foliar chemistry on the net per capita rate of increase in a gypsy moth population. If relative consumption rate per larva is unaffected by herbivory, a reduction in the nutritional value of foliage reduces the net rate of increase at relatively low larval densities, and increases the larval density needed to bring about starvation. This result is achieved by reducing larval assimilation efficiency, or by increasing larval death rate, or both, in response to declining nutritional value of foliage associated with herbivory. An increase in relative consumption rate in response to herbivory reduces the larval density needed to bring about starvation, and reduces the net rate of increase of the larval population at all higher larval densities.

Introduction

Oak (*Quercus* spp.) foliage is the principal food of the gypsy moth (*Lymantria dispar* (L.)) in Eastern North America. Herbivory causes changes in the concentrations of suspected primary and secondary metabolites in gypsy moth in the foliage of oaks (Schultz and Baldwin, 1982; Valentine et al., 1983). Late-instar gypsy moths that feed on severely defoliated oaks are smaller at pupation, and less fecund, than gypsy moths that feed on essentially undefoliated trees (Wallner and Wilton, 1979). Together, these results suggest that changes in foliar chemistry induced by herbivory influence the population dynamics of gypsy moth during outbreaks and the subsidences of outbreaks. The exact nature of the influence is neither known nor obvious because it is intermingled with the influences of parasites, predators, disease, and food shortage. However, it should be possible to discern some of the effects of induced changes in foliar chemistry on gypsy moth population dynamics through modeling.

The Model

The basic model that I use consists of a system of differential equations. The equations describe changes in larval dry weight, larval

abundance, and available foliage with respect to time measured in days (t), where 1 day is assumed to equal 15 Celsius degree days (threshold = 4.4°). The equations are initialized at the start of each larval generation and solved over the interval $0 \leq t \leq 44$. It is assumed that all larvae hatch and start feeding coincident with budbreak at $t=0$, and that all surviving larvae pupate at $t=44$. The values of the components at $t=44$ are used to predict the initial values of the components for the next generation. For example, the initial number of larvae next year is predicted from the number of pupae this year.

The variables of the model are:

$W(t)$ = average dry weight of a larva (mg)
 $F(t)$ = expected dry weight of a leaf (mg)
 $F^*(t)$ = total amount of foliage available (mg)
 $X(t)$ = number of gypsy moth larvae feeding on $F^*(t)$

$C_{\max}(t)$ and $C_{\text{act}}(t)$ are maximum and actual consumption rates (mg/day) of the larval population, which are defined in terms of the variables of the model.

The variables are related as follows:

$$C_{\max} = a_1 W X \quad (1)$$

$$C_{\text{act}} = \min(C_{\max}, a_2 F^*) \quad (2)$$

$$dX/dt = -X(a_3 + a_4(1 - C_{\text{act}}/C_{\max})) \quad (3)$$

$$dW/dt = E(C_{\text{act}}/X) - a_5 W \quad (4)$$

$$dF/dt = a_6 F(\ln F)(1 - (\ln F)/a_7) \quad (5)$$

$$dF^*/dt = (F^*/F)dF/dt - C_{\text{act}} \quad (6)$$

In the absence of a shortage of food, the consumption rate of a larva is $a_1 W$ (Valentine and Talerico, 1980), and the consumption rate of the larval population (C_{\max}) is $a_1 W X$ (eq. 1). If the consumptive demand of the larval population approaches or exceeds available foliage (i.e., $C_{\max} > a_2 F^*$), herbivory is constrained at rate $a_2 F^*$ (eq. 2), and the consumption rate of a larva is $a_2 F^*/X$.

Since gypsy moth is univoltine, and dispersal is assumed nil, all changes in the abundance of feeding larvae are negative. By equation (3), larvae die at rate a_3X from the effects of density-dependent agents, and, during a food shortage, larvae cease to feed (and starve) at rate $a_4(1-C_{act}/C_{max})X$.

Average larval growth (eq. 4) is equal to the average larval anabolic rate minus the average larval catabolic rate (a_5W). The anabolic rate is the product of the larval consumption rate (C_{act}/X) and assimilation efficiency (E). Foliage quality should influence larval growth through its effect on E ; various predictors of E are described in the next section.

Equation (5) describes the growth of an average-size leaf (Valentine, 1983), and equation (6) describes the collective growth of (say) N leaves available to the larval population. In the absence of larval feeding, the relative rates of increase in dry weight in the average leaf and the N leaves are equal (i.e., $dF^*/F^*/dt = dF/F/dt$), and the solutions of (5) and (6) are related as $F^*(t) = NF(t)$. When the gypsy moth feeds, the growth of available foliage is reduced by the rate of consumption (C_{act}), and $F^*(t) < NF(t)$ for $t > 0$. Rationale for the formulation of (6) was reported by Goldstein and Van Hook (1972), Nagy (1978), and Valentine (1978). Apparent herbivory (H) can be calculated from the solutions of (5) and (6) as:

$$H = (1 - (F^*(t)/N)/F(t)) \quad (7)$$

The solution of equation (5) can be written as

$$\ln F(t) = a_7/(1 + \exp(a_8 - a_6t)) \quad 0 \leq t \quad (8)$$

Therefore, (5) can be eliminated from the model by substituting for $(dF/dt)/F$ on the right hand side of (6) with:

$$(dF/dt)/F = a_6a_7(\exp(a_8 - a_6t)/(1 + \exp(a_8 - a_6t)))^2 \quad (9)$$

At budbreak ($t=0$), average leaf dry weight is

$$F(0) = \exp(a_7/(1 + \exp(a_8))) \quad (10)$$

To initialize $F^*(t)$, it is convenient to put the variables of the model on a per-ha basis. If we denote the asymptotic dry weight of mature foliage per ha as F^*_{max} , then total available foliage at budbreak is:

$$F^*(0) = F(0)F^*_{max}/\exp(a_7) \quad (11)$$

To solve the model over a period of years, a function is needed that predicts initial larval abundance ($X(0)$) in year $n+1$ from pupal abundance ($X(44)$) in year n , viz.:

$$X(0)_{n+1} = a_9W(44)_nX(44)_n \quad (12)$$

The parameter a_9 subsumes survival rates of pupae, adults, and eggs, and the proportion of females in the adult population; egg production is a linear function of pupal weight (Hough and Pimentel, 1978).

Solutions of the Model

One way to discern the effects of food quality on gypsy moth population dynamics is to compare solutions of the model with and without the effects of food quality included, while holding other effects constant. Unless noted otherwise, the following solutions were computed with the parameter values listed in table 1, and with $W(0) = 0.2$ mg, and $F^*_{max} = 10^5$ mg/ha.

Assuming that food quality is invariant between years and unaffected by herbivory, a purely empirical expression describing assimilation efficiency of larvae for eq. (4) is the cubic polynomial (adapted from Valentine and Talerico, 1980):

$$E = a_{10} + a_{11}t + a_{12}t^2 + a_{13}t^3 \quad (13)$$

The model of gypsy moth abundance without food quality effects is now completely defined.

Inspection of the model shows that where food is unlimited, the net per capita rate of increase (1/yr) in the abundance of feeding larvae (X) from $t=0$ in year n to $t=0$ in year $n+1$ is constant:

$$\ln(X(0)_{n+1}/X(0)_n) = -a_344 + \ln(a_9) + \ln(W(44)_n) \quad (14)$$

When the initial larval density in year n is sufficient to cause a food shortage, the right hand side of (14) no longer applies, as the net per capita rate of increase declines precipitously (Fig. 1). Over a period of years, $X(0)$ assumes a pattern such as depicted in Figure 2; i.e., $X(0)$ increases exponentially from year to year until food becomes limiting to late-instar growth and survival, causing a catastrophic decline in $X(0)$ the following year, and a resumption of exponential population increase. However, it is evident in Figure 1 that the net per capita rate of increase can be zero, so a steady state population is theoretically possible.

As was noted, herbivory causes changes in foliar chemistry which reduce larval growth and pupal weight. We can produce such an effect by forcing larval assimilation efficiency to decrease as herbivory increases. The only change we need to make is to substitute E' for E in (4) where

$$E' = E(1 - a_{14}H) \quad 0 < a_{14} < 1 \quad (15)$$

Under the assumptions and constraints of the model, it is obvious that this function will cause per capita fecundity to decline with increased herbivory, because fecundity is a

Table 1.--Values of parameters used to generate solutions of the model.

Parameter	Value	Source of value or data
a_1	1.003	Valentine and Talerico (1980)
a_2	0.5^a	Sensitivity Analysis
a_3	0.08	Campbell (1981)
a_4	4.0^a	Sensitivity Analysis
a_5	0.0192	Valentine and Talerico (1980)
a_6	0.265	Valentine (1983)
a_7	6.109	Valentine (1983)
a_8	0.893	Valentine (1983)
a_9	2.5	Campbell (1981)
a_{10}	0.2885	Valentine and Talerico (1980)
a_{11}	-1.0635×10^{-2}	Valentine and Talerico (1980)
a_{12}	2.4861×10^{-4}	Valentine and Talerico (1980)
a_{13}	-2.3609×10^{-6}	Valentine and Talerico (1980)

^aValues of a_2 and a_4 were guessed and then adjusted to give larvae that survived starvation a reasonable dry weight.

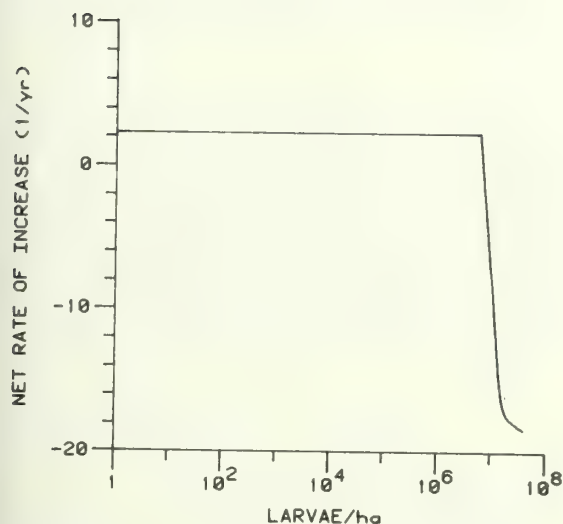


Figure 1.--Net rate of increase in larval density versus larval density as predicted by the model without foliage quality effects included.

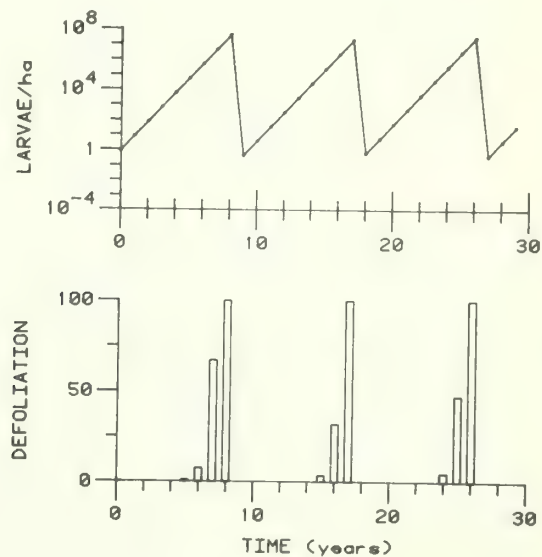


Figure 2.--Time-series of larval densities and defoliation as predicted by the model without foliage quality effects included.

linear function of pupal weight. The effect of this function on the net per capita rate of increase of the population is less obvious, but as shown in Figure 3 for a_{14} equal to 0 (no effect), 0.09, and 0.18. On the basis of experimental results reported by Wallner and Walton (1979) and by Valentine et al. (1983), I estimate the true value of a_{14} to be 0.09.

At relatively low initial larval densities, the net per capita rate of increase (for $a_{14} > 0$) is less than the corresponding rate that would be expected in the absence of a larval response ($a_{14}=0$) to changes in foliar chemistry induced by herbivory (Fig. 3). However, at relatively high larval densities, the net rate of increase is greater with a

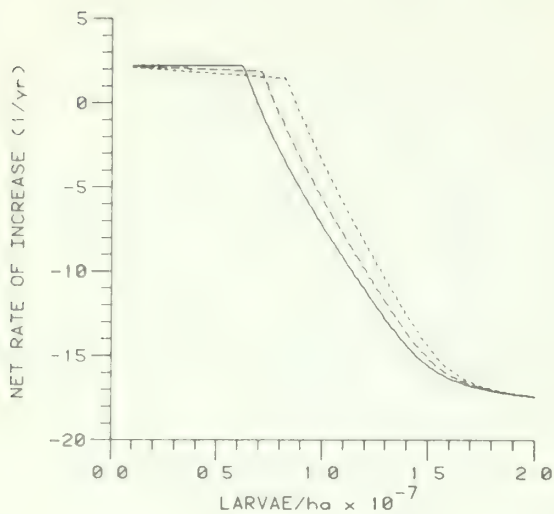


Figure 3.--Net rate of increase in larval density versus larval density when a reduction in larval assimilation efficiency associated with herbivory is included in the model (see eq. (15)). The 3 curves represent no response to herbivory (solid, $a_{15}=0.0$), the estimated true response to herbivory (long dash, $a_{15}=0.09$), and an exaggerated response to herbivory (short dash, $a_{15}=0.18$), respectively.

response to herbivory because fewer individuals die from starvation. Average larval consumption rate is proportional to larval weight, so starvation becomes less likely at a given population density if larvae respond to herbivory with a reduction in assimilation efficiency, but no change in relative consumption rate. The relatively inefficient assimilators weigh less than they would in the absence of the response and, therefore, are less likely to eat all the available foliage. Consequently, a reduction in larval abundance due to starvation may be postponed by a year, affording the gypsy moth additional opportunity to spread its infestation through the dispersal of first instars. The reduction in the net rate of increase in response to herbivory also tends to reduce the chance of starvation during the early instars of the next generation, and increase the chance that a larva will live to pupation. Therefore, reductions in the population through starvation may be smaller with a response to herbivory than without one. At very high initial larval densities, the model indicates that changes in foliar chemistry have virtually no effect on the net rate of increase.

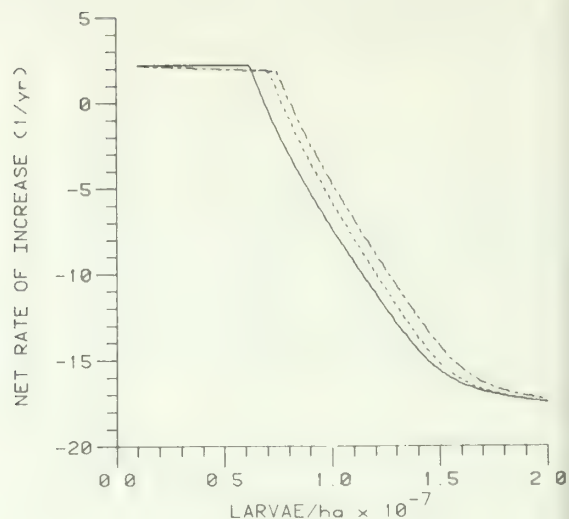


Figure 4.--Effects on herbivory on the net rate of increase in larval density. No effect (solid line); reduced assimilation efficiency with no change in relative consumption rate (short dash), and no change in assimilation efficiency, but a reduction in relative consumption rate (short dash, long dash).

The most plausible explanation for the decline in larval growth associated with herbivory is a reduction in larval assimilation efficiency. However, it is possible that assimilation efficiency is unaffected and larvae simply reduce their feeding rate in response to herbivory. The models for the two cases are similar, but not identical. Assuming no food shortage, where assimilation efficiency is affected by herbivory, we have

$$C_{\max} = a_1 WX \quad (17)$$

and

$$dW/dt = E(1-a_{14}H)a_1W-a_5W \quad (18)$$

If feeding rate is reduced, but assimilation efficiency is unaffected, we have

$$C_{\max} = a_1(1-a_{14}H)WX \quad (19)$$

and

$$dW/dt = Ea_1(1-a_{14}H)W-a_5W \quad (20)$$

Thus, in both cases, larval growth (dW/dt) is the same. However, the feeding rate (C_{\max}) of the larval population declines with herbivory in the latter case and, therefore, larval death due to starvation is less likely at a given larval density (Fig. 4).

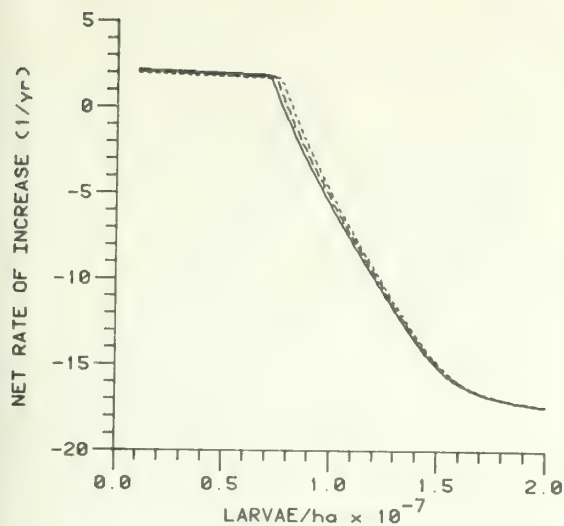


Figure 5.--Net rate of increase in larval density versus larval density when the effect of defoliation in the prior year (long dash) or 2 prior years (short dash) is added to the model (see eq. (21)). Both curves are estimated true responses. No effect due prior defoliations is represented by the solid line.

Additional reductions in pupal weight and fecundity due to consecutive defoliations (as reported by Wallner and Walton, 1979) tend to exacerbate the response of the larval population to herbivory in terms of its net per capita rate of increase (Fig. 5). The effects shown in Figure 5 were achieved by replacing a_{10} in eq. (13) with a_{10}' where

$$a_{10}' = a_{10} - a_{15}H(44)_{n-1}(1+H(44)_{n-2}) \quad (21)$$

A parameter value of $a_{15} = .002$ gives percentage reductions to $W(44)_n$ due to defoliations in year $n-1$ and year $n-2$ consistent with the results of Wallner and Walton (1979). The implicit assumption here is that changes in foliar chemistry due to defoliation in the prior year or 2 prior years affects the assimilation efficiency of larvae in the current year. If we solve the model over a period of years, the time series of $X(t)$ is similar to that shown in Figure 1 that it does not warrant a figure of its own. However, the more or less constant 9-year cycle shown in Figure 1 becomes an alternating 8- or 9-year cycle when food quality effects are added.

It has been hypothesized that changes in foliar chemistry induced by herbivory increase the rate of death of larvae from malnutrition, parasitism, and disease (e.g., Podgwaite, 1981; Shultz and Baldwin, 1982). If we assume that the per capita death rate increases with herbivory, we can assess the consequences of this larval response by replacing a_3 on the right hand side of eq. (3) by a_3' where

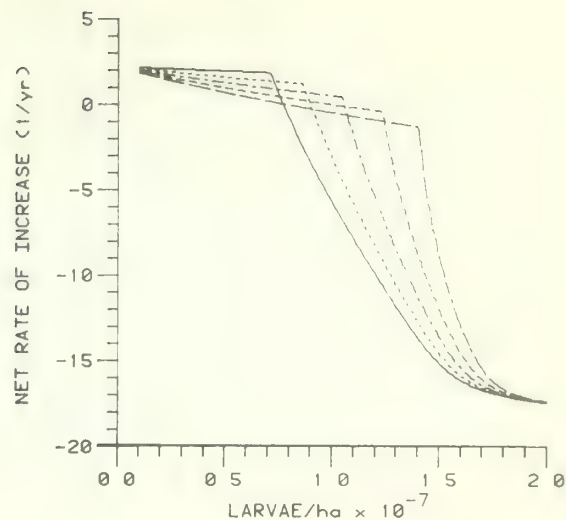


Figure 6.--The effect of an increase in larval death rate associated with herbivory (see eq. (22)) on the relation between net rate of increase in larval density and larval density for $a_{16}=0.0$ (solid), 0.02 (short dash), 0.04 (dot dash), 0.06 (mid-sized dash), and 0.08 (longest dash).

$$a_3' = a_3 + a_{16}H \quad (22)$$

The effect of an increase in larval death rate associated with herbivory on the net rate of increase of the population is shown in Figure 6 for a_{16} equal to 0 (no effect), 0.02, 0.04, 0.06, and 0.08. The result is a familiar one; the net rate of increase of the population is reduced by the increase in death rate until the larval density is reached where starvation would be manifested in the absence of the increase. At higher larval densities, the net per capita rate of increase is greater because reductions in the population due to starvation are either postponed or buffered by death of larvae from other causes. Indeed, when a_{16} was assigned a value of 0.06 or 0.08, the increased death rate associated with herbivory effectively prevented the population from growing large enough to collapse from starvation (Fig. 7); instead, the population settled into a steady state. As a_{16} is increased further, the steady-state population is smaller and severe defoliation is prevented, but this is contrary to our experience with gypsy moth.

It is not known whether gypsy moth larvae respond to a reduction in the nutritional value of foliage with an increase in relative consumption rate, but Scriber and Slansky (1981) indicated that tree feeders are limited in their ability to do this. The only structural change we need to make to the model to assess the effects of increased larval consumption rate is to replace a_1 in eq.

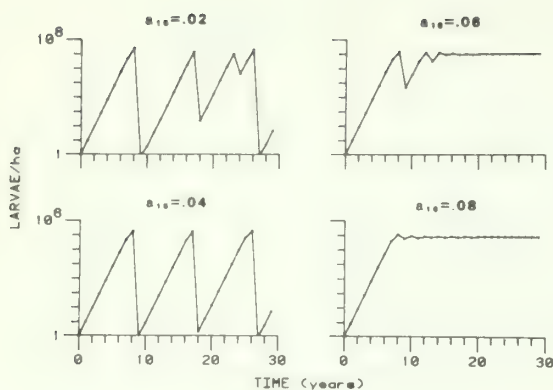


Figure 7.--Time-series of larval densities with increases in larval death rate associated with herbivory included in the model.

(1) by a_1' where

$$a_1' = a_1 + a_{17}H \quad (23)$$

Any increase in consumption rate associated with herbivory requires a compensatory reduction in assimilation efficiency so that $W(44)$ will equal its expected value. Thus, the parameter a_{14} of eq. (15) will vary directly with a_{17} , though not linearly. The effect of this hypothesized larval response on the net per capita rate of increase of the larval population (given $a_{16}=0$) is shown in

Figure 8 for $a_{14}=0.09$, $a_{17}=0$; $a_{14}=0.18$,

$a_{17}=0.1$; $a_{14}=0.26$, $a_{17}=0.2$; and $a_{14}=0.40$,

$a_{17}=0.4$. At low larval densities, where herbivory is negligible, the effect of the larval response on the net rate of increase also is negligible. However, increases in larval consumption rate reduce the larval density needed to bring about starvation, and reduce the net rate of increase of the larval population at all higher larval densities.

Summary and Conclusions

If the parametrization of the model is adequate, the following conclusions can be drawn from this analysis. Where larval density is insufficient to cause starvation, larval response to herbivory results in a reduction in per capita fecundity, which singly, or in combination with increased larval death rate, reduces the net rate of increase in gypsy moth abundance. Unless larval relative consumption rate increases in response to herbivory, the net rate of increase in gypsy moth abundance is

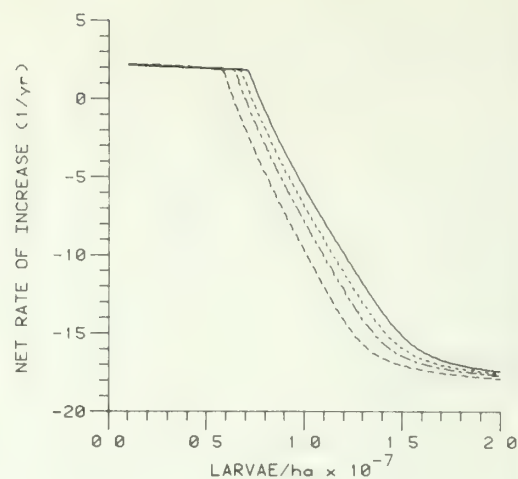


Figure 8.--Net rate of increase in larval density versus larval density where larval relative consumption rate increases with herbivory (see eq. (23)). Solutions are plotted for $a_{17}=0$ (solid), 0.1 (dot), 0.2 (dot-dash), and 0.4 (dash).

greater at all larval densities where larval starvation would ensue in the absence of any larval response, because a reduction in assimilation efficiency or feeding rate--or an increase in larval death rate--in response to herbivory effectively reduces the cumulative consumption of the larval population. If larval relative consumption rate does increase in response to herbivory, then, compared to no increase, the larval density needed to bring about starvation is reduced and the net rate of increase is reduced at all higher densities.

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Although it may soon be possible to alter stand foliage quality and thus reduce budworm reproductivity, the impact of such changes on the budworm-forest system remains unclear. There are currently a number of hypotheses concerning the key biological mechanisms which drive the budworm-forest system. The possible effects of changes in foliage quality are examined for four such alternative hypotheses. Each hypothesis suggests that in the short-term reducing foliage quality will lengthen the interval between outbreaks, increase the rate of stand wood volume production, and increase outbreak severity--and overall, improve the budworm problem in economic terms. The situation for the long-term is less certain: in some circumstances reducing foliage quality may even aggravate the budworm problem from an economic viewpoint.

Introduction

The eastern spruce budworm, *Choristoneura fumiferana* (Clem.), is a naturally outbreaking defoliator of spruce (*Picea* spp.) and balsam fir (*Abies balsamea* [L.] Mill.) in the boreal forests of eastern North America. Epidemic populations severely defoliate their host trees over wide areas causing reduced growth, top kill, and tree mortality which often results in considerable economic difficulties for the forest industry (Irland 1980).

Aerial application of insecticide has been the principal means of controlling budworm damage since the early 1950's. However, concerns about environmental impacts and cost-effectiveness (e.g., Swenson 1980) have motivated a search for possible alternative control methods. It has long been recognized that stands differ in their likelihood of budworm damage (Balch 1946; Morris 1963, pp. 189-292) and more recently it has been observed that several important nutritional parameters vary with needle age, tree species, stand maturity and other factors affecting budworm development and density (Kimmins 1971; Shaw et al. 1978; White 1974). As a consequence it has been suggested that certain stand characteristics could be manipulated through selective breeding (e.g., Zobel 1982) or fertilizer application (e.g., Shaw et al. 1978) to "favorably" alter budworm-forest dynamics. But before much investment in such research, it seems prudent to anticipate how changes in stand characteristics might affect the budworm-forest system.

This paper explores the impacts that changes in one such stand characteristic, foliage quality, might have on budworm-forest dynamics. Here foliage quality refers to the rate at which increases in foliage consumption per budworm are accompanied by increases in budworm reproductivity.

Anticipation of the effects of reducing foliage quality requires some understanding of the biological mechanisms underlying budworm-forest dynamics. Currently, there is considerable disagreement regarding the relative importance of these mechanisms. Blais (1974) concludes that budworm outbreaks require extensive areas of mature stands of balsam fir; Baskerville (1976) and Jones (1979) stress the effects of background predators; Stedinger (1977) suggests that all outbreaks are triggered by moth invasions; and Royama (1982) implies that a complex of numerically responding parasitoids and diseases may be a "universal cause" of budworm oscillations. Baskerville, Blais, Jones, and Stedinger assume that the depletion of food and ovipositing sites resulting from defoliation and tree mortality cause outbreak collapse.

Figure 1 illustrates the assumed interactions between the principal components of the

Key : B = Budworm
E = Budworm's Natural Enemies
F = Foliage
W = Wood Volume

---- Impact of Minor Importance
—— Impact of Major Importance

Note: Arrows Indicate Direction of Impact

TREE MORTALITY

B ↔ F ↔ W

'FAST' ENEMIES

E ↔ B ↔ F ↔ W

MOTH INVASION

E → B ↔ F ↔ W

'SLOW' ENEMIES

E → B ↔ F ↔ W

Figure 1. Hypotheses concerning the underlying mechanics of budworm-forest dynamics. The major components and their interactions are shown.

budworm-forest ecosystem for four hypothetical outbreak generating mechanisms. The 'tree mortality' hypothesis (Blais 1974) implies important and reciprocal impacts between budworm and foliage, and between foliage and wood volume. In the 'slow enemies' hypothesis,

Baskerville (1976) and Jones (1979) suggested that polyphagous non-synchronized predators and parasites limit the increase of low density budworm populations. Between outbreaks, these background enemies maintain their numbers by feeding on alternate prey as well as on budworm. During outbreaks, the numbers of budworm enemies increase much more slowly than budworm numbers so 'per capita' budworm losses to predation and parasitism decrease substantially. The lack of an arrow pointing from budworm to its slow enemies in Figure 1 reflects the assumed insignificance of the slow enemy numerical response to budworm densities.

Stedinger's (1977) moth invasion hypothesis (Fig. 1) encapsulates the behavior of his large scale simulation model of budworm-forest dynamics. In contrast to Baskerville and Jones, he concluded that the impact of natural enemies on budworm-forest dynamics was less important than that of moth invasion in terms of driving the outbreak cycle. According to his model, invasion is a prerequisite for outbreak: without it, low density mortality factors extinguish small budworm populations. Sufficient budworm invasion raises local populations to densities where these mortality factors are less important; population increase then continues until outbreak levels are reached, even in the absence of further moth immigration.

The 'fast' enemies hypothesis of Figure 1 represents a simplification of the conclusions Royama (1982) reached after reanalysing the Green River Project data (Morris 1963). According to Royama, mortality due to the combined action of parasitoids, pathogens, and a complex of unknown causes "apparently associated with the occurrence of disease(s) of an unknown nature is the most probable universal cause of population oscillation". The implication is that the mortality associated with certain synchronized parasitoid and pathogen populations increases quickly enough during budworm outbreaks to return budworm populations to low densities before resource limitation necessarily becomes important. Since budworm population collapse deprives these fast natural enemies of their principal food, fast enemy populations fall soon afterwards. A pattern of oscillations in natural enemy - budworm population sizes typical of predator-prey relationships (e.g., Krebs 1972, pp. 247-254) arises.

In what follows, I study the effects of reducing foliage quality on budworm-forest dynamics for each hypothesis illustrated in Figure 1. I hope to identify the range of impacts that can be expected on both a short and a long term basis.

A Simple Budworm-Forest Model

I begin by introducing a simple idealized model of the budworm-forest ecosystem. It will provide a standard of comparison by which to consider the complexity of budworm-forest dynamics in the field. Adopting a philosophy akin to that of laboratory work, the model is deliberately simplified so that the effects of reducing

foliage quality on budworm-forest dynamics can be examined in isolation. My approach is deductive: using data reported in the literature and assumption when data is lacking, I mathematically describe various aspects of the budworm-forest ecosystem; then, using computer simulation, I deduce the logical consequences of these mathematical descriptions.

The Forest Submodel

The model as a whole is intended to describe the dynamic relationships between budworm density, B , foliage quantity, F , and wood volume, W , in a representative balsam fir stand in Maine. To simplify model development, I initially ignore the budworm and concentrate solely on stand growth. Although the physiology of stand growth is poorly understood, the limited evidence available suggests that the annual increments of wood volume and foliage generally increase with the rates of photosynthesis and growth hormone production (Kramer and Kozlowski 1979). Since both these physiological processes occur in the foliage and use light energy captured by the foliage (Kramer and Kozlowski 1979), the model treats foliage as the 'engine' driving stand growth.

Stands use captured light for the maintenance of existing biomass as well as for the production of new biomass. Given the lack of knowledge about how captured light is partitioned between these processes, I assume a simple linear relationship (after Smith 1963). This linearity is evident in the following description of the relative rate (U) at which the stand 'consumes' captured light in year t to $t + 1$:

$$U = m.F(t) + g [F^*(t + 1) - F(t)] \quad (1)$$

$F(t + 1)$ is starred to indicate that it represents the potential stand foliage quantity in year $t + 1$ in the absence of budworm. The coefficients m and g represent the respective ratios of captured light allocated to maintenance and growth. It is implicitly assumed in this equation that foliage quantity is linearly related to stand biomass. The fact that the curvature of the relationship between wood volume and foliage quantity (Fig. 2) is small over realistic ranges suggests that this assumption may not be an unreasonable approximation. (For future reference, Table 1 alphabetically lists algebraic symbols used throughout the paper).

I also assume that in the absence of budworm, the annual 'per capita' rate of increase of stand foliage is proportional to A , the relative availability of limiting factors. It follows that the ratio of stand foliage quantities in successive years t and $t + 1$ can be written

$$F^*(t + 1)/F(t) = R.A + 1 \quad (2)$$

where R is the proportionality factor, the maximum annual 'per capita' rate of foliage production possible, and $F^*(t + 1)$ is the potential stand foliage quantity in year $t + 1$ in the absence of budworm.

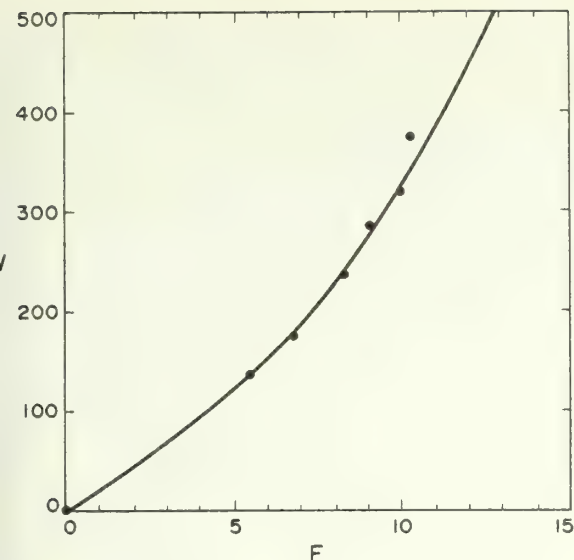


Figure 2. Wood volume, W (in m^3/ha) plotted against foliage surface, F (in $10^4 \text{ m}^2/\text{ha}$). Solid circles indicate the means of field observations (Baskerville, 1965, Tables 5 and 9) averaged over every $50 \text{ m}^3/\text{ha}$ interval of W starting from $W = 0$. The curve illustrates equation (6).

In light-limited conditions, A can be simply expressed as

$$A = 1 - U/U_{\max} \quad (3)$$

where U_{\max} denotes the maximum rate at which the stand uses captured light. The existence of U_{\max} follows from the existence of an upper bound on foliage quantity (Fig. 2). Hence, if F_{\max} represents the maximum foliage quantity a stand can sustain, it follows from equation (1) that

$$U_{\max} = m \cdot F_{\max} \quad (4)$$

Substituting equations (1) and (4) into (3), substituting the result into (2), and then rearranging, the ratio of stand foliage quantities in successive years in the absence of budworm becomes

$$\frac{F(t+1)}{F(t)} = \frac{1 + R \cdot (1 - F(t)/F_{\max})}{1 + Z \cdot F(t)} \quad (5)$$

where $Z = R \cdot g / (m \cdot F_{\max})$. The parameter Z represents the maximum possible ration of captured light for foliage growth relative to the maximum for tree maintenance.

The economic value of a harvestable stand depends on its wood volume, and its wood volume, in turn, depends on its foliage quantity (Fig. 2). Expressing the relationship shown in Figure 2 mathematically:

$$W(t) = 544 F(t) / [268000 - F(t)] \quad (6)$$

where wood volume, W , is measured in m^3/ha . For consistency with the rest of the paper, the units of foliage quantity in Figure 2 have been converted from the originally reported kg/ha to m^2 of foliated branch surface per ha. This conversion was accomplished by comparing Baskerville's (1965) data of F in kg/ha against W (for immature stands) with Morris' (1955, p. 287) data of F in ft^2/acre in stands 35 and 55 years old. By relating stand age to W through Figure 3 and assuming that stands of equal wood volume generally have equal foliage, it was estimated that .193 kg of foliage are the equivalent of a m^2 of foliated branch surface.

Table 1. Definitions of algebraic symbols*

A	relative availability of limiting factors (-)
B	budworm density (egg masses/ m^2 of foliated branch surface)
B_I	egg masses/ m^2 deposited by invading moths (B)
B_N	egg masses/ m^2 deposited in the stand by 'native' moths (B)
C	foliage to budworm conversion efficiency (B)
D	fraction of current foliage destroyed by budworm (-)
F	stand foliage quantity (m^2 of foliated branch surface/ha)
F_{\max}	maximum stand foliage quantity possible (F)
F_S	foliage quantity of typically susceptible stands (F)
g	fraction of 'captured' light used for stand growth ($1/F$)
L	amount of defoliation (F)
M	annual wood volume loss through tree mortality (-)
m	fraction of 'captured' light used for tree maintenance ($1/F$)
n	indicates the influence of foliage on budworm ovipositioning (-)
Q	foliage quality (-)
R	maximum annual 'per capita' foliage production (-)
t	time (years)
U	relative rate by which the stand consumes captured light (-)
U_{\max}	maximum value U can attain (-)
W	stand wood volume (m^3/ha)
W_M	stand wood volume when tree mortality begins (W)
W_{\max}	maximum stand wood volume possible (W)
Z	ratio of the maximum possible ration of light for foliage growth relative to the maximum for tree maintenance ($1/F$)

* Parentheses following definitions enclose the dimensionality; e.g. $1/F$ indicates that g is measured in ha/m^2 of foliated branch surface and - indicates A is dimensionless.

The assumption that the data reported in Figure 3 are appropriate for a representative balsam fir stand in Maine is implicit in this conversion of foliage units. The observation

that previous budworm outbreaks have left much of eastern North America's spruce/fir forest in a relatively even-aged condition (Baskerville 1976, p 8; Seymour 1980, pp 91-109) lends some support to this assumption. Whether data from a fully-stocked stand is representative is less certain.

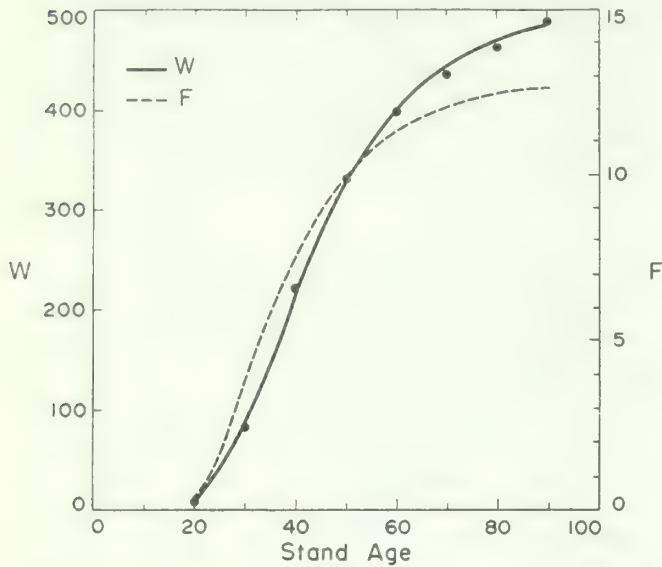


Figure 3. Wood volume, W (in m^3/ha), and foliage quantity, F (in $10^4 \text{ m}^2/\text{ha}$), plotted against age (years) for a fully-stocked even-aged balsam fir stand. The observations (solid circles) were taken from a good site (stand height = 18.3 m at age 65) in the northeast U.S. (Bakuzis and Hansen, 1965, Table 96). The solid and dashed lines show output of the forest dynamics submodel, equations (6) and (7), in the absence of budworm. These simulations began at $t = 20$ with $W = 9.1$.

Together, equations (5) and (6) constitute the foundation of the model's description of stand growth in the absence of budworm. A more specific description requires estimates of the parameters F_{max} , R , and Z .

Extrapolation of the field data of wood volume against stand age in Figure 3 indicates a maximum stand wood volume of about $W_{\text{max}} = 500 \text{ m}^3/\text{ha}$. Although the physiological mechanisms limiting volume growth to $W \leq W_{\text{max}}$ are unknown, various observations are suggestive. First, the ratio of respiring tissue (e.g., stem cambium) to photosynthesizing tissue (foliage) increases with age (Möller et al. 1954). Second, translocation becomes more difficult as distances from the roots to the foliage increase with tree height (e.g., Kramer & Kozlowski 1979, pp 610-611). Third, mature stands generally exploit site 'carrying capacity', as reflected in light, water, and nutrient availability, more fully than very young stands (Baskerville 1965, p 2). But regardless of the physiological mechanism involved, given $W_{\text{max}} = 500 \text{ m}^3/\text{ha}$, it follows from equation (6) that $F_{\text{max}} = 128400 \text{ m}^2/\text{ha}$.

To estimate the parameters R and Z , numerical solutions to equation (5) with $F_{\text{max}} = 128400 \text{ m}^2/\text{ha}$ were computed for various combinations of R and Z . These solutions were translated into time series of wood volumes through equation (6) and compared to the field observations of Figure 3. A search for an acceptable series of standardized residuals (Devore 1982, p. 459-464) and a low sum of squared residuals produced estimates of $R = .47$ and $Z = .00005$ to two and one significant figures, respectively; the extra significant figure reflecting the model's greater sensitivity to R . Hence, according to equation (5), the ratio of gross (i.e., before accounting for defoliation) foliage to the previous year's net (i.e., after accounting for defoliation) foliage is

$$\frac{F^*(t+1)}{F(t)} = \frac{1.47 - 3.6 \times 10^{-6} F(t)}{1 + .00005 F(t)} \quad (7)$$

Figure 3 shows that in the absence of budworm, the forest submodel, equations (6) and (7), can describe wood volume growth reasonably well. However, confidence gained in the forest submodel from the results displayed in Figure 3 is limited because three parameters (R , W_{max} , and Z) were estimated from these data.

Defoliation

Completion of the forest submodel requires that the impacts of the budworm on the forest through defoliation and tree mortality be defined. Figure 4 illustrates the relationship

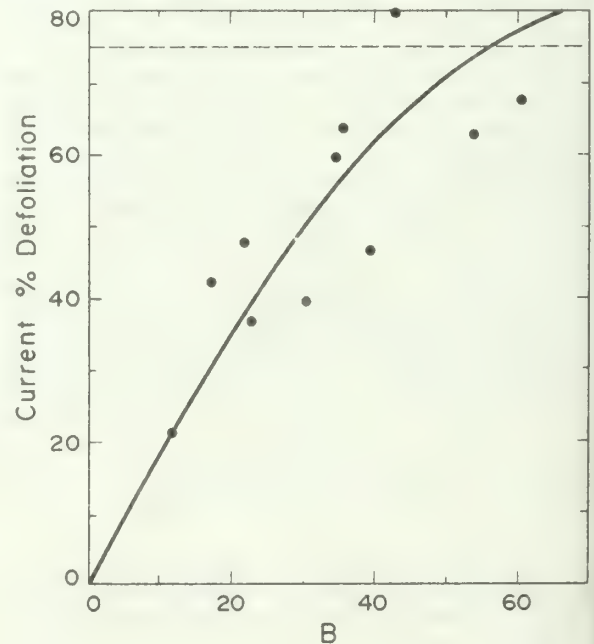


Figure 4. Plot of the % defoliation of new foliage against the number of new, healthy, budworm egg-masses per m^2 of foliated balsam fir branch surface. The solid circles show Miller's (1977, Fig. 3) data; the solid curve illustrates equation (8). Current defoliation is 75% along the dashed line.

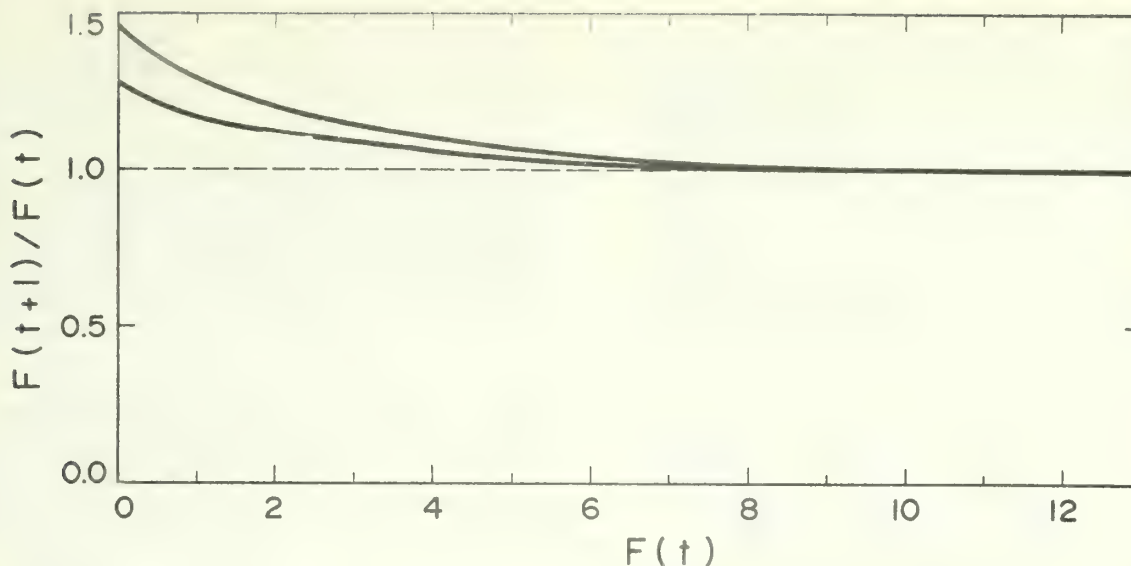


Figure 5. Foliage recruitment ratio, $F(t+1)/F(t)$, plotted against stand foliage quantity in year t , $F(t)$, in $10^4 \text{ m}^2/\text{ha}$. The upper and lower solid curves distinguish foliage recruitment ratios for budworm densities of 0.0 and 25.8 egg-masses/ m^2 , respectively. $F(t+1) = F(t)$ along the dashed line. The curves illustrate the system of equations: (7), (9), and (10).

between current defoliation and budworm egg mass density reported by Miller (1977, Fig. 3). The curve has been visually drawn to represent his data and to pass through the origin (since no defoliation is expected without budworm). The equation

$$D(t+1) = 1.82 B(t)/(B(t) + 84) \quad (8)$$

describes this curve where $D(t+1)$ is the fraction of current foliage destroyed in year $t+1$ by budworm larvae surviving from a population of B egg-masses/ m^2 in year t . Taking current foliage as $F^*(t+1) - F(t)$, it follows from equations (7) and (8) that the total amount of foliage destroyed by budworm in year $t+1$, $L(t+1)$, relative to the stand foliage in year t , $F(t)$, is

$$\frac{L(t+1)}{F(t)} = \frac{1.82 B(t)}{B(t) + 84} \times \frac{.47 - .000054 F(t)}{1 + .00005 F(t)} \quad (9)$$

Baskerville (1965, p 15) suggests $.25 F^*(t+1)$ as an alternative measure of the amount of current foliage. The implications of this possibility are presently under investigation.

Equation (9) completes the model's description of stand foliage dynamics when tree mortality is not a factor. The model computes net foliage as a function of budworm density and net foliage in the previous year from

$$F(t+1) = F^*(t+1) - L(t+1) \quad (10)$$

where gross foliage, $F^*(t+1)$, and losses to budworm, $L(t+1)$, are given by equations (7) and (9), respectively. The model then calculates $W(t)$

$+1$ from equation (6), thus reflecting Peinés' (1980) conclusion that "balsam fir...growth reductions are expressed the same year as the first defoliation occurs".

Figure 5 illustrates the model's description of foliage dynamics for budworm densities of 0 and 25.8 egg-masses/ m^2 . This latter density represents the borderline between the 'moderate' and 'high' infestation classes of the Maine Forest Service (Fleming et al. 1983); it corresponds to 43% current defoliation (Fig. 4). The foliage recruitment ratio is a decreasing function of both foliage and budworm density.

Tree Mortality

Tree mortality usually begins after three to six years of "persistent, severe defoliation" (MacLean 1981) through some unknown physiological mechanism (Kramer and Kozlowski 1979, pp 676-677). Taking 'severe' defoliation as exceeding 75% current defoliation (after Baskerville and MacLean 1979), the model triggers the tree mortality process in the fifth consecutive year of budworm densities above 58.9 egg-masses/ m^2 (the density corresponding to 75% current defoliation in Fig. 4).

Once tree mortality begins, foliage is no longer the 'engine' driving wood production. Rather, the model reduces total stand foliage roughly in proportion to, and as a consequence of, losses in W , the wood volume contributed by live trees. (Since W excludes wood volume contributed by dead trees, using W to indicate stand value ignores any possible profit from salvage operations.)

If M is the fractional loss of wood due to tree mortality in any year while tree mortality is occurring, then the fractional survival rate is $1-M$. Therefore, since tree mortality continues for six consecutive years in a representative stand (MacLean 1981, Fig. 1), stand wood volume at the completion of tree mortality is

$$W(t_M + 6) = (1-M)^6 W(t_M)$$

where t_M is the year when mortality began. Algebraic manipulation of this equation shows that

$$M = 1 - \exp (.167 \ln[W(t_M + 6)/W(t_M)]).$$

MacLean (1981, Fig. 1) suggests that once triggered, cumulative tree mortality (in number of stems) reaches about 99% in mature stands and 55% in immature stands after six years. Since mortality in number of stems generally provides a reasonable approximation to mortality in wood volume (MacLean 1980), it follows from the equation above that $M = .54$ and $.12$ for mature and immature stands, respectively. Wood volumes corresponding to mature and immature stands were estimated from Baskerville and MacLean (1979, Table 7) as $450 \text{ m}^3/\text{ha}$ and $135 \text{ m}^3/\text{ha}$, respectively. Thus the model can use stand wood volume at the onset of tree mortality, W_M , as an indicator of stand age. A simple expression fitting these observations and the constraint that $M = 0$ when $W_M = 0$ is

$$M = 10^{-6} W_M^2 + .00075 W_M. \quad (11)$$

Summarizing, the model's tree mortality process begins in the fifth consecutive year of budworm densities exceeding $58.9 \text{ egg-masses}/\text{m}^2$ and continues for six years causing an annual volume loss of $M \times W$. The model treats the fractional loss of wood volume due to tree mortality, M , as a function of the stand's wood volume when tree mortality started, W_M . While tree mortality is occurring, foliage is calculated through the inverse of equation (6).

The Budworm Submodel

Although the spruce budworm - forest system has periodically been the object of intensive investigation, many questions remain to be answered regarding the reciprocal impacts between the budworm and its hosts. These uncertainties are necessarily reflected in the following submodel of budworm dynamics. This submodel is meant to provide a simple qualitative description of budworm population dynamics: it can claim to be neither definitive nor quantitatively accurate. Nonetheless, it will provide a useful basis for discussing the qualitative impacts of changes in foliage quality.

The development of the budworm submodel begins by distinguishing between the eggs laid by moths invading the stand and those 'native' to the stand. If B is the budworm density (in egg masses/ m^2 of foliated branch surface) then the annual change in budworm density is

$$B(t+1) - B(t) = B_N + B_I - B(t) \quad (12)$$

where B_N and B_I are the egg masses/ m^2 deposited in the stand by budworm which develop within and outside the stand, respectively. Thus B_N and B_I represent the egg deposition in the stand by 'native' and invading moths. The last term on the right side of equation (12) represents budworm mortality. Its form reflects the maximum budworm longevity of about 13 months local extinction must exist, at least temporarily, following a complete lack of oviposition within the stand (i.e., when $B_N = B_I = 0$).

Indirect evidence (Greenbank et al. 1980; Miller 1979; Morris 1963) suggests that dispersing moths favor stands with many large mature, well-foliated balsam fir trees for oviposition. Miller et al. (1978) estimated that moths invading a heavily sprayed test block from the surrounding infested forest deposited about $10 \text{ masses}/\text{m}^2$. But budworm are reportedly rare between outbreaks (Baskerville 1976; Morris et al. 1958) so B_I is likely small in most stands lacking suitable foliage. Accommodating these assumptions and observations, the budworm immigration density can be expressed as an exponentially increasing function of foliage quantity:

$$B_I(t) = 10[F(t)/F_S]^n$$

where F_S represents the foliage quantity in a typical susceptible stand and n is a yet to be determined exponent indicating how abruptly immigration increases with increases in stand foliage.

Balch (1946) reports that moderately and highly susceptible stands generally exceed 40 and 60 years of age, respectively. Accepting the mean age of 50 years, the model assigns typically susceptible stands an average foliage quantity of $F_S = 10^5 \text{ m}^2/\text{ha}$ in accordance with Figure 3. Then, given respective practical maximums for B_I of $1.2 \times 10^5 \text{ m}^2/\text{ha}$ (Fig. 2) and $20\text{-}30 \text{ egg masses}/\text{m}^2$ (Miller et al. 1978), $n = 5$ to the nearest integer satisfies the expression for B_I above. Hence, the annual egg mass deposition by invading moths becomes

$$B_I(t) = 10 [F(t)/10^5]^5 \quad (13)$$

The density of egg masses deposited by native moths, $B_N(t)$, also depends on stand foliage, $F(t)$. Assuming the total number of eggs deposited by native moths in year t , $B_N(t)F(t)$, is proportional to the foliage consumed $L(t)$,

$$B_N(t) = C.L(t)/F(t)$$

where C is the foliage to budworm conversion efficiency (i.e., the egg masses produced per m^2 of foliated branch surface destroyed). Since larval survival and moth fecundity reportedly increase as stand maturity increases (Morris et al. 1958; Morris 1963, p 189-202), and since moth fecundity declines exponentially as the duration of sustained severe defoliation increases (Morris

1963, pp 85-87), C is likely an increasing function of foliage. A simple possibility is

$$C = Q[F(t)/F_s]^n$$

where Q represents foliage quality in terms of budworm reproductivity and n is an unspecified exponent determining how sharply C accelerates as $F(t)$ increases. Combining the last two equations, and recalling that the amount of foliage of typical susceptible stands is $F_s = 10^5 \text{ m}^2/\text{ha}$, the annual egg mass deposit by native moths becomes

$$B_N(t) = Q \cdot L(t) \cdot F(t)^{n-1} / 10^{5n} \quad (14)$$

Equation (14) completes the model: equations (12), (13), and (14) constitute the budworm dynamics submodel; equation (11) describes the tree mortality process; equations (7), (8), and (9) link the budworm and forest submodels through defoliation, and equations (5) and (6) comprise the forest growth submodel.

Values for n and Q , however, remain undetermined in equation (14). Simulations of the complete model with initial conditions $W = 9.1 \text{ m}^3/\text{ha}$ (Fig. 3), $F = 4409 \text{ m}^2/\text{ha}$ [equation (6)], and $B = 1.7 \times 10^{-6} \text{ masses/m}^2$ [equation (13)] and with various values of n and Q displayed a variety of different outbreak cycles. Realistic cycles are generally 26-40 years in length (Royama 1982) with outbreaks lasting 6-15 years

in relatively unmanaged forests (Baskerville 1976; Stedinger 1977) and with budworm densities varying over four orders of magnitude (Baskerville 1976). Since $Q = .06$ and $n = 5$ produced the cycles which best met these criteria and which had a realistic range (c.f. Fleming et al. 1983) of budworm egg mass densities, these values were adopted as reference points for other simulations.

Model behavior, however, may also be acceptable for very different values of n and Q . Nonetheless, this is unlikely to affect the range of qualitative behavior exhibited by the model as Q varies: the model is behaviorally consistent for changes in n (excluding n values which do not admit acceptable outbreak behavior). Therefore, since this paper deals only with the qualitative behavior of the model, such behavior will be discussed only for $n = 5$ below.

A final comment on the form of equation (14) - the function $B_N(t)$ represents the product of the survival of the local population from eggs in year $t-1$ to moths in year t times the local reproductivity of those moths. Moreover, the (generation) survival component of $B_N(t)$ is itself the product of the survival rates for each of the six larval instars. Hence, since many of these instar survival rates probably increase with foliage (Thomson 1979), there is some theoretical basis for writing $B_N(t)$ as a function of $F(t)$ raised as high as the fourth power.

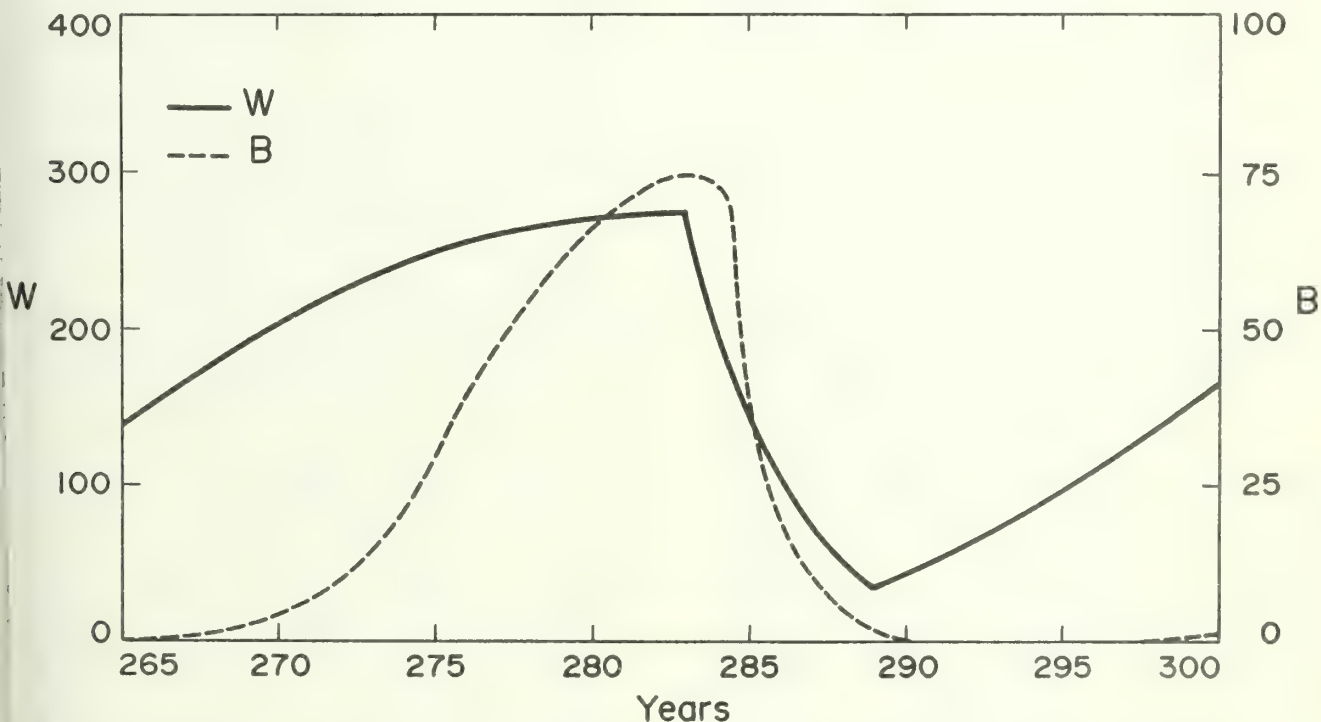


Figure 6. The 33-year outbreak cycle produced by the full model under 'natural' foliage quality conditions (i.e., $Q = .06$). Wood volume, W , and budworm density, B , are shown for years 265-300 of a numerical solution to equations (5)-(9), (11)-(14) with $n = 5$. The simulation began in year 20 with $W = 9.1 \text{ m}^3/\text{ha}$ and $B = 1.7 \times 10^{-6} \text{ egg-masses/m}^2$.

Figure 6 illustrates the behavior of the model through a typical outbreak cycle. Beginning at $t = 265$, both budworm density (B) and foliage increase with time, changes in foliage being reflected (through Fig. 2) by the wood volume (W) curve in Figure 6. Foliage increases favor the budworm population [cf. equations (12)-(14)] which grows in response. But as it grows it destroys more foliage (Fig. 4), thus reducing the foliage and volume increments. By $t = 280$ the budworm population has become so large (over 58.9 masses/m²) that current defoliation exceeds 75% [equation (8)]. Tree mortality, equation (11), begins in the fifth consecutive year ($t = 284$) of such severe defoliation and decimates the wood volume and foliage during the next six years. The budworm population crashes in response to the consequent loss of feeding and oviposition sites. By $t = 289$ most of the overstory has been destroyed (low W) and the immature, relatively less vulnerable understory trees are beginning stand regeneration.

When foliage quality, Q , is reduced 50% from its value of .06 in Figure 6, (and nothing else is changed), the model exhibits a very different behavior: the outbreak cycles are replaced by a state of apparent equilibrium with the budworm density, B , stable at 35 masses/m² and the wood volume stable at its maximum of 500 m³/ha. Curiously, this reduction of foliage quality allows both the budworm and the wood volume to maintain greater long term averages than they did in Figure 6: the budworm density does not get high enough for long enough to trigger the tree mortality process. The reduction in foliage quality acts to slow budworm increase during its population growth phase ($265 < t < 280$ in Fig. 6) and this prevents prolonged severe defoliation before the budworm population declines in response to reduced foliage levels. Hence, tree mortality seems necessary for the model to exhibit outbreak cycles; this is the basis of the tree mortality hypothesis of outbreak generation.

The foregoing analysis deserves two qualifications. First, stands don't last forever even without budworm: they deteriorate with age and become susceptible to fire, diseases, and other pests. Hence, the 'apparent equilibrium' is more properly viewed as a long-term regeneration cycle; budworm-caused tree mortality short-circuits the cycle. Second, model behavior is not independent of its starting point: for particular values of Q ($n = 5$) the model could exhibit both outbreak cycles and apparent equilibria depending on the initial conditions. These qualifications also apply to Table 2.

Table 2 summarizes the results of model simulations beginning at $t = 20$ with $W = 9.1$ m³/ha and $B = B_I = 1.7 \times 10^{-6}$ masses/m² for various values of Q . (Figs. 3 and 6 correspond to the runs for $Q = .03$ and .06, respectively.) Reducing foliage quality (Q) has a number of benefits for the forest manager: increasing peak wood

Table 2. The effect of foliage quality on model behavior.

Foliage Quality (Q)	Outbreak Cycle Period (years)	B^1 (masses/m ²)	W^1 (m ³ /ha)
.6	19	225.1	163.1
.1	27	98.46	236.6
.065	32	78.55	267.9
.06	33	75.00	274.5
.055	35	72.81	283.4
.05	37	69.79	293.3
.045	40	67.25	306.0
.04	44	64.41	322.1
.035	52	62.43	347.1
.03	55 ²	58.66	398.2
.01	55 ²	32.31	449.1
.0	55 ²	27.71	458.7
.0 ³	55 ²	0 ³	484.6 ³

¹ B and W columns list the outbreak cycle maximums when $Q \geq .035$ and the 90-year values when $Q \leq .03$.

²Quasi steady state behavior - no outbreaks.

³No budworm immigration (i.e., $B_I = 0$).

volume, decreasing peak budworm densities, and lengthening the outbreak cycle period (realistically, steady states represent long-term regeneration cycles). Reducing foliage quality can also have detrimental effects. First, it lengthens outbreak duration (defined as the period during which $B > 25.8$ masses/m²) although this effect is usually small and not in proportion to the period lengthening. Second, tree mortality is more severe as a consequence of the greater maximum wood volumes [equation (11)]. However, further reductions of foliage quality (e.g., $Q < .03$ in Table 1) can prevent budworm outbreaks from occurring at all. Hence, the major consistent effects of reducing foliage quality in this model are increases in maximum wood volume and decreases in budworm outbreak frequency.

Other Hypotheses of Outbreak Generation

The models underlying various outbreak hypotheses are conveniently compared in terms of recruitment ratios, the ratios of budworm densities in successive years in the absence of moth immigration. For instance, according to equations (12)-(14), $B_N(t)/B(t)$ approximates the recruitment ratio for the tree mortality model. Curves a and b of Figure 7 show that this ratio increases with stand foliage and decreases with budworm density. Curve b shows that when the stand is immature ($F = 70000$ m²/ha), $B(t+1)/B(t) < 1$ so the native budworm population declines steadily. But as the stand matures (F increases) the recruitment rate rises until $B(t+1) > B(t)$ at small densities (e.g., curve a). The native population can then increase up to its equilibrium density (the density at which the recruitment curve crosses the dashed line); for curve a, 68 masses/m². At densities above and

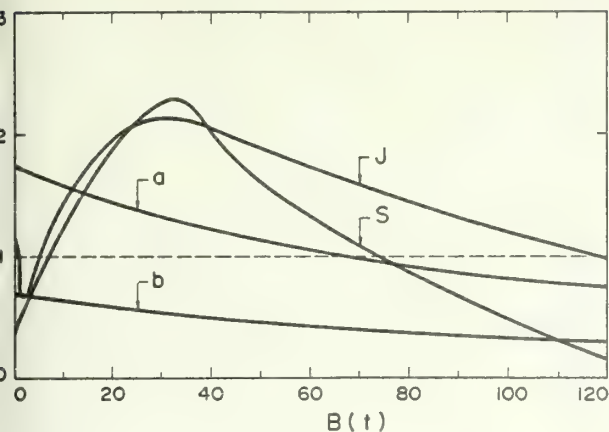


Figure 7. Budworm recruitment ratios, $B(t+1)/B(t)$, when immigration is negligible plotted against budworm density in year t , $B(t)$, in egg-masses/ m^2 . Curves a and b distinguish ratios for foliage quantities of 90000 and 70000 m^2/ha , respectively, in the model developed above. Curves J and S respectively represent ratios for Jones' (1979) and Stedinger's (1977) models. Equilibria occur wherever the curves cross the dashed line, $B(t+1) = B(t)$.

Below this equilibrium the population decreases and increases, respectively. Hence, the equilibrium is stable: any slight deviation from the equilibrium density will be followed by a return to it.

Curve S in Fig. 7 typifies recruitment ratios for Stedinger's (1977) model; equilibria occur at 6 masses/ m^2 and 74 masses/ m^2 . The lower equilibrium is unstable: slightly smaller densities lead to a continued decrease, slightly larger ones to a continued increase. Hence, in Stedinger's model, a sparse population cannot grow of its own accord; moth invasion is needed to raise the budworm density above the unstable equilibrium density, in which case, an outbreak is inevitable.

Curve J in Figure 7 illustrates the budworm recruitment curve in a stand with moderately favorable conditions in Jones' (1979) model. Stable equilibria occur at 1 and 118 masses/ m^2 and an unstable equilibrium occurs at 5 masses/ m^2 . However, as in the tree mortality model, stand conditions determine the elevation of the entire curve. When the dip in the recruitment curve at low densities eventually clears the dashed line in response to improved stand conditions, the two lower equilibria vanish allowing budworm to increase quickly to outbreak densities. The resulting forest destruction is reflected in the drop of the entire curve below the dashed equilibrium line and this signals the ensuing collapse of the budworm population. Subsequent stand regeneration causes the slow

elevation of the budworm recruitment curve but the next outbreak does not occur until the dip at low densities has again cleared the dashed equilibrium line.

Although stochasticities introduced by weather and moth invasion also play a role, it is clear that the low density dip, the so-called 'predator pit', dominates the behavior of Jones' model. The predator pit represents the assumed effect of a group of background natural enemies (principally birds) whose relatively small reproductive potential prevents their populations from keeping pace with budworm increases during outbreaks. This predator pit is the basis for the slow enemies hypothesis of outbreak generation attributed to Baskerville (1976) and Jones (1979) in Figure 1.

Reducing foliage quality has similar effects on the qualitative dynamics of each of the models discussed in detail above. Equation (14) shows that foliage quality, Q , determines the height of the recruitment curve, $B_N/B(t)$, at any given budworm density for the tree mortality model. Hence, for given forest conditions and budworm densities, decreasing foliage quality lowers the height of the recruitment curve and hence reduces the propensity for budworm increase. The result is a reduction of the frequency and severity of outbreaks (Table 2). Analogously, reducing foliage quality can be expected to lower recruitment curves (Fig. 7) for both Stedinger's model and Jones' model. Consequently, more immigrant moths would be needed to trigger an outbreak in Stedinger's model and greater stand maturity (larger F values) would be needed to overcome the effect of the predator pit and initiate an outbreak in Jones' model. Hence, for both these models, reducing foliage quality can be expected to reduce budworm outbreak frequencies and increase maximum wood volumes. But, since tree mortality increases with maximum wood volume, reducing foliage quality and thus extending the period between outbreaks results in greater stand destruction when outbreaks do occur (see also Casti, 1982).

The effects of reducing foliage quality are less certain for the fast enemies hypothesis of budworm outbreak generation. According to this hypothesis, certain budworm parasitoid and pathogen populations increase so fast in response to increased budworm densities during outbreaks that they subsequently decimate the budworm populations, thus ending the outbreaks. The complexity of such a system and the uncertainties regarding the attributes of the mortality factors make it particularly difficult to predict how it will respond to reductions in foliage quality. Nonetheless, given these reservations, longer intervals between outbreaks, greater wood supplies, and more severe outbreaks can be expected in the short-term. However, in the long-term, reducing foliage quality may have some undesirable effects. For instance, parasitoid and pathogen populations which lack sufficient alternate hosts and are unable to maintain their populations on low budworm populations during the

longer intervals between outbreaks may become exceedingly rare. Thus freed of these parasitoids and pathogens, the budworm might become an even greater pest than it had been before foliage quality was reduced.

Summary and Conclusions

The consequences of reducing foliage quality on spruce budworm dynamics have been discussed for four hypotheses of outbreak generation (Fig. 1). These hypotheses differed with respect to the principle biological mechanism underlying budworm outbreaks: tree mortality (Blais, 1974), slow natural enemies (Baskerville 1976; Jones 1979), fast natural enemies (adapted from Royama 1982), and moth invasion (Stedinger 1977). Despite these differences, the analysis indicated that the immediate consequences of reducing foliage quality should be similar for each hypothesis: increasing maximum wood volume, decreasing outbreak frequency, and increasing outbreak severity. The first two consequences offer benefits for forest management: increasing maximum wood volume implies an increase in the economic value of the stand at cutting time; decreasing outbreak frequency implies that a stand need be cut less often to preclude budworm-caused tree mortality, and therefore that the economic costs of harvesting could be reduced.

In the long-term it is clear that the budworm would face extinction given sufficient reduction of foliage quality. More modest and more realistic expectations for foliage quality reductions would have the budworm always present. The long-term consequences should then be similar to the short-term consequences for each hypothesis with two possible exceptions. First, if some of the fast natural enemies cannot maintain viable populations during the longer intervals between budworm outbreaks, short-term 'improvement' of the budworm problem may be followed by its long-term 'aggravation': greater outbreak frequency and smaller maximum wood volumes. Second, the possibility of genetic adaptation by the budworm to changes in foliage quality has not been considered. Suffice it to say that the budworm, with a one year generation time, appears to have the potential to adapt quickly enough to cause problems. Perhaps agriculture can suggest a solution to this potential problem: cultivar mixtures, multilines, and horizontal resistance (e.g., Fleming and Person 1978, 1982) have each been proposed as means of incorporating crop resistance against short-generation plant pathogens.

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CHARACTERISTICS OF STANDS SUSCEPTIBLE AND RESISTANT TO GYPSY MOTH DEFOLIATION

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Site conditions strongly influence where
gypsy moth defoliation will occur. In New
England, where gypsy moths and forests have
interacted for over a century, some forests
have had a history of repeated defoliation
while others have been defoliated only rarely.
Often defoliated or susceptible forests
characteristically grow on dry sites such as
rocky ridges or deep sands. In many cases,
they have been disturbed--sometimes
frequently--by fire, wind, snow, or ice storms.
The trees in these forests, mainly dry-site
species, often are highly favored as food by gypsy
moths, are slow growing, small, and scrubby,
and have abundant structural features such as
bark flaps, deep bark fissures, and holes or
cavities that are used as resting sites by gypsy
moths.

The open nature of susceptible forests
encourages the growth of plants such as
blueberry, huckleberry, bracken, sweetfern,
sedges, and sedges. Leaf litter usually is
shallow or lacking; on ridge stands, surface
rocks or exposed ledges are common.

Resistant forests where defoliation is
rare are characteristically grow on relatively
undisturbed sites with well-drained, deep loam
soils where moisture is not limiting. They
usually are well stocked and contain mixtures
of species, including some that are highly
preferred. Trees on these sites have good
growth rates and relatively few structural
features used by gypsy moths.

Understory plants in New England's
resistant forests include such species as wild
sage, sassafras, maple-leaved viburnum, and
woodland ferns. Resistant stands have deep
litter layers that are favorable habitat for
many predators of gypsy moth.

It is not axiomatic that trees growing on
susceptible sites are more apt to succumb to a
given defoliation regimen than trees on
resistant sites. Studies suggest that trees on
adverse sites may be no more--indeed, may even
be less vulnerable--than trees on good sites.
Perhaps this reflects, at least in part, the
fact that trees on poor sites represent the
survivors of an exceptionally intense and
continual selection process. Other
relationships that are probably involved
include the relative energy demands of small,

slow-growing trees compared to large
fast-growing ones; the amounts and conditions
of substrates that support fungi and insects
that attack and kill defoliation-stressed trees.

These descriptions of susceptible and
resistant stands in the Northeast represent the
extremes of a range of susceptibilities. It is
likely that stands will be susceptible if they
are on adverse sites and contain high
proportions of preferred tree species with
abundant refuges. It is also likely that
well-stocked, mixed, fast-growing stands free
of recent disturbance will be resistant, and
will suffer damaging defoliation only upon
disturbance or upon invasion by a large number
of larvae from adjacent areas.

But stands at opposite ends of the
susceptibility spectrum are not always, indeed
not usually, encountered. In New England, many
intermediate stands on mesic sites are changing
from susceptible to resistant as their natural
development is accompanied by decreases of
highly preferred species and by proportionate
increases of less preferred species.
Intermediate stands that contain sizable
proportions of highly preferred food species
can be rendered more susceptible by
disturbances that "open them up" and favor once
again the more light-demanding food species
that are preferred by the gypsy moth. Such
disturbance also can reduce the impact of
ground-inhabiting gypsy moth predators by
removing or drying out the litter and soil
habitat so important to these animals' survival
and by creating above-ground protective refuges
for the insect on the trees.

We often refer to susceptible stands,
particularly those on ridges, as focal sites,
and research and observations have indicated
that gypsy moths do spread from such stands to
surrounding more resistant forests. Probably
susceptible stands should also be considered
as focal areas for the processes that
contribute to release of gypsy moth populations.
Conceptually, susceptible stands that are under
more or less continuous moisture stress and
disturbance support the systems for population
release that are expressed in more "buffered"
resistant forests following periods of water
shortage or disturbance.

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SPRUCE BUDWORM AND SPRUCE-FIR STANDS

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Abstract. The impact of the budworm on trees and stands and conditions that lead to susceptible and vulnerable stands are discussed. Long-term and short-term options dealing with the spruce budworm problem are presented. Examples of questions that plant-animal interaction research have answered are presented in the following scenarios: (1) can the release of an outbreak be detected, (2) can spruce budworm impact be predicted, (3) are region-rating systems accurate, and (4) what, if any, relationships exist between site classification units and spruce budworm impact.

Introduction

The North American boreal forests have experienced periodic spruce budworm outbreaks for hundreds of years. Although the spruce budworm is an integral component of spruce-fir forests in North America, it normally does not prevent the continuity of spruce-fir forests. Spruce and spruce usually regenerate after an outbreak, reaching a merchantable size in 40 to 60 years.

The spruce budworm was not considered a major problem in eastern North America until 40 years ago. Expansion and addition of numerous sawmills and paper mills led to greater market demand for spruce and fir. More intensive forest management practices were needed to meet demand and to reduce the amount of impact from the spruce budworm on spruce-fir stands. Forest management practices had to be based on a thorough understanding of the interactions between budworms and forests under a variety of management scenarios.

As researchers, we understand the value of forest studies involving plant-animal interactions in forest ecosystems. However, we have not done a very good job in justifying this kind of research to the applied forestry community. Hopefully, this paper and others presented at the workshop will help show how both basic and applied studies on plant-animal interactions are needed if we are going to provide the land manager with sound forest pest management programs. This paper is divided into three sections: biological information, management options, and forecasting scenarios involving plant-animal interactions.

Insect impact is any effect that insect activity has on a forest resource. Impact can be described as having a positive effect, a negative effect, or no effect. Damage implies a harmful or negative effect. Land managers are usually interested in the evaluation of this negative effect.

The interaction between the spruce budworm and the spruce-fir forest involves the effect of the budworm on the forest and the effect of the forest on the budworm. The terms susceptibility and vulnerability have been applied to these interactions. Susceptibility is the probability that a stand will be attacked by the budworm. Vulnerability is the probability of tree mortality in the stand once a budworm attack occurs. In this section, we describe the impact of the budworm on trees and stands and conditions that lead to susceptible and vulnerable stands.

Impact on Trees and Stands

Budworm impact includes growth loss, cone and seed mortality, top-kill, tree and stand mortality, changes in stand composition, and various interactions between the budworm and other organisms in the forest (Table 1). Studies on growth loss in North America have shown a 30 to 90 percent reduction in radial growth in spruce-fir stands heavily defoliated by the spruce budworm for 2 to 6 years (MacLean 1981). A considerable increase in balsam fir cone and seed mortality occurs during an outbreak; few sound seeds are produced during a severe outbreak (Hudak and Raske 1981). Top-kill usually begins during the third year of an outbreak. The total number of dead tops often reaches 50 percent or more. Fir trees in the codominant and dominant crown classes usually die after about 5 years of repeated defoliation of current year's growth. Complete stand mortality can occur after 7 to 10 years of continuous heavy defoliation. Mortality in mature fir stands usually ranges from 70 to 100 percent, while mortality in immature stands varies from 30 to 70 percent (MacLean 1980). Budworm attack can result in changes in stand composition (Ghent et al. 1957, Turner 1952). However, spruce budworm destroyed forests usually regenerate with spruce and fir. Repeated removal of current year's needles by the budworm results in reduced tree vigor and subsequently makes the trees more susceptible to bark beetles and fungi (Basham and Belyea 1960, Belyea 1952). The impact of spruce budworm attack may be transitory or long-lasting (Batzer 1969, Blais 1958).

Conditions Leading to Susceptible and Vulnerable Stands

Any spruce-fir stand or host tree in eastern North America is susceptible to a spruce outbreak. As a general rule, certain factors usually increase the amount of volume loss and tree mortality in a spruce-fir stand during a

Table 1. Succession of events associated with a spruce budworm outbreak, on balsam fir (modified from Montgomery et al. 1982).

Years of severe defoliation ^{a/}	Impact
1	Flowers and cone crops die. Radial growth loss occurs in the upper crown.
2 to 3	Small roots begin to die. Radial growth loss occurs over the entire stem. Height growth ceases. Some treetops die.
4 to 6	Suppressed trees in the understory and mature and overmature trees in the overstory begin to die. Tree growth and wood production nearly ceases.
7 to 15	Budworm populations begin to collapse. More trees die, particularly balsam fir. Some seedlings and saplings die. Dead trees begin to deteriorate as a result of disease, secondary insect attack, and wind breakage. Protective cover in deer yards is diminished.

^{a/} 75 percent or more of current year's growth.

budworm outbreak (Table 2). Stand mortality usually increases with the duration and severity of the outbreak. Percent tree mortality is greatest in stands with the highest proportion of balsam fir followed in descending order by white, red, and black spruce. Mortality is usually much higher in stands greater than 60 years old. Open stands in which spike tops of host trees protrude from the forest canopy often suffer more damage. Stands on abnormally dry or wet sites usually sustain more damage.

The factors presented in Table 2 usually hold true, but there is great variation within the boreal forest (Mog et al. 1982, Blais 1968). For more information, Witter et al. (1983) presented a detailed review on the impact of the budworm on trees and stands.

Management Options

From a land manager's perspective, nothing can be done to prevent or control a regional outbreak of the spruce budworm since management

Table 2. Factors that increase the amount of damage (volume loss and tree mortality) in a spruce-fir stand (from Witter et al. 1983).

General factor	Conditions leading to severe damage
Intensity and duration of outbreak	Stand mortality usually increases with the severity and length of outbreak.
Species composition	Stands with large balsam fir components have greater potential for mortality than stands comprised mostly of spruce and hardwoods.
Stand age	Mature fir stand (60 years or older)
Stand density	High basal area of balsam fir, red spruce, and white spruce
Stand structure	Open stands in which spike tops of host species protrude from forest canopy
Site condition	Poorly drained stands, abnormally dry or wet
Stand size	Extensive stands of mature host trees (except black spruce)
Stand location	Stands located downwind (often east) of the current outbreak
Topography and latitude	Stands growing at elevations lower than 2300 ft (700 m) and south of 50° latitude

actions are directed at individual stands (Simmons et al. 1983). There are three types of options available to the land manager: (1) actions directed at the stand (i.e., silvicultural techniques), (2) actions directed at the budworm (i.e., microbial or chemical insecticides), or (3) no action. None of these management options will result in the control of a regional outbreak.

The land manager can influence the time, place, and quantity of mortality that will occur in his or her forest. Various intensive forest management practices reduce spruce-fir vulnerability by replacing budworm-prone forests with less susceptible forest types. The following recommendations are good long-term goals (Flexner et al. 1983):

- (1) Shorten the rotation age of fir to 50 years or less.
- (2) Break up the continuity of extensive areas of mature forest.
- (3) Maintain a mixed-species composition whenever feasible.

Convert the stand to less susceptible species.
) On a regional basis, optimize the spatial diversity of different even-aged stands.

Research on plant-animal interactions will help to plan better forest management approaches for reducing future budworm impact. However, even the best approach will never prevent budworm outbreaks.

Once an outbreak occurs, short-term options are available to help protect or to harvest the trees in the most seriously threatened stands through salvage operations and spraying valuable stands with microbial or chemical insecticides.

Using biological information, the land manager can rank the probability of damage to his or her stands. Salvage operations can be conducted first in the highest risk stands. A land manager may decide to spray an insecticide on the most valuable mature spruce-fir stands that are heavily attacked by the budworm and may die within a few years. If markets are poor, the land manager may choose to abandon the stand.

Interesting Scenarios Involving Plant-Animal Interactions

Current studies are helping land managers and researchers to better understand interactions between the budworm and spruce-fir forests. These studies have and will continue to produce techniques to reduce the amount of budworm-prone forests and to provide more environmentally sound techniques to reduce the impact of the budworm on the forest. Four scenarios are presented to show the examples of some of the questions that research on plant-animal interactions have answered or are trying to answer.

Scenario 1: The Release Phase Of An Outbreak Can Be Detected -- Yes, No, Maybe

In studying the current outbreak in Quebec, Gossard et al. (1983) found that the outbreak started in seven epicenters. All were located in mixed-wood stands that included sugar maple, yellow birch, and white pine. Softwoods, about 10 years of age, occupied less than 30 percent of the stand. Ecological disturbances such as fire and logging occurred in all epicenters. The outbreak was first detected in areas with mature balsam fir. Also, the major front of the outbreak was preceded by the establishment of a cluster of infestation centers distributed in an east-west pattern. If we can locate epicenters, early detection of incipient outbreaks may make modification of management plans possible.

An understanding of where epicenters may occur could be helpful to pest management specialists responsible for monitoring budworm populations. The use of a pheromone sampling system to monitor low population levels of the

spruce budworm is now feasible (Allen and Dorais 1983). The pheromone sampling system is currently being pilot-tested in eastern North America. This type of sampling system, when it becomes operational, will allow a land manager to detect an increase in the budworm population as many as five years prior to noticeable defoliation.

Scenario 2: Spruce Budworm Impact Can Be Predicted -- Yes, No, Maybe

Land managers must be able to predict the type and amount of damage from the budworm to effectively manage their stands. A number of rating systems (both short-term and long-term) have been developed to assist the forest manager in determining the vulnerability of the forest to budworm attack (McCarthy et al. 1983, 1982; Blais 1975; Batzer 1973, 1969; Graham 1956; Bean and Batzer 1956; Westveld 1954, 1945; Morris and Bishop 1951; McIntock 1948, 1949; Balch 1946). Budworm impact can be predicted.

Many of the rating systems currently in use in eastern North America concentrate on short-term objectives. These rating systems are used to help managers determine which stands need to be salvaged or sprayed during the next year or two.

An example of a short-term rating system using 35mm aerial photographs is described by Olson et al. 1982. This system is based on the proportion of host species within the stand, average tree condition ranking for the stand, and the existing percent mortality of host species. The land manager uses the stand-rating mortality of host species. The land manager uses the stand-rating value for each stand to plan which stands should be salvaged or protected during the next several years. The system also has been adapted and used with a 70mm camera system.

Long-term rating systems are based on the concept of vulnerability and are used to help the land manager reduce the vulnerability of the forest over time. Lynch, Fowler, and Witter developed a long-term rating system for Michigan's Upper Peninsula to predict the amount of balsam fir basal area per hectare that will die due to the budworm. Factors which influenced budworm impact in the Upper Peninsula were: (1) the length of time the outbreak has been in progress in different parts of the Peninsula, (2) the quantity of balsam fir present in the stand, (3) stand species composition, (4) site factors, particularly drainage, and (5) past and present land management practices. This rating system will provide the land manager in the Upper Peninsula of Michigan with a useful management tool by estimating potential losses. The estimates can be used to plan preventive, presalvage, and salvage harvesting programs. The system can be easily implemented by land managers because the necessary data are readily available from routine compartment examinations and inventory systems.

The rating systems developed so far do not have high predictive accuracy throughout the insect's entire range or have not been tested over the insect's entire range. However, a rating system developed to help the land manager determine the vulnerability of the forest to budworm attack at the management unit level in eastern Canada is compatible for both New Brunswick and Quebec (MacLean 1982, Blais and Archambault 1982). Their vulnerability index provides a rating based on the combined volume of balsam fir and white spruce, combined volume of black and red spruce, the maturity of balsam fir, and climate. This system depends on the availability of forest inventory data and is not fully operational at this time. Long-term rating systems in the Great Lakes Region do not appear to be compatible over the entire Region. For example, Lynch, Witter, and Fowler had to use five models to predict the amount of balsam fir basal area per hectare that will die due to the spruce budworm in the Upper Peninsula of Michigan. Their system differs from the system developed by Batzer and Hastings (1981) for Minnesota. The answer to the question on whether region-wide rating systems are accurate appears to vary by region. The land manager must be very careful about using any rating system that has not been validated for his or her area.

Scenario 4: There Is A Relationship Between Site Classification Units and Impact From The Spruce Budworm -- Yes, No, Maybe

Stand mortality is not evenly distributed within a state or province. These differences may be partially due to site conditions. A number of site classification systems are currently being developed in North America. A logical approach is to break an area into ecosystem units that are consistently found in the stand. These ecosystem units can be distinguished by differences in physiography, soils, and vegetation (Barnes et al. 1982). Individual characteristics such as topography, drainage, aspect, slope, depth of organic matter, soil pH and texture, and plant species groups may be incorporated into a site classification scheme. Hix et al. (1983) developed a classification system for spruce-fir stands in the Ottawa National Forest in Michigan's Upper Peninsula based on site and vegetative characteristics. Currently, the possible relationships between site classification units and damage is being analyzed. This type of study helps determine if there are relationships between sites, the budworm, and damage.

Final Discussion

If we are going to manage the forest in a way that is both ecologically sound and financially rewarding, a thorough understanding of the interactions between the budworm, site

conditions, and stands is necessary. Progress has been made during the last decade in building a knowledge base as shown by the scenarios in this paper and in the other papers presented at this workshop. The implementation of this knowledge base has already resulted in improved management decisions. We must continue to support long-term studies on plant-animal interactions in order to further improve our knowledge base and decision making abilities.

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Spruce budworm larvae grew faster than gypsy moth larvae both in a temporal and relative sense. The budworm larvae had a higher relative growth rate (RGR), biomass conversion efficiency (ECI), and nitrogen utilization efficiency (NUE) than the gypsy moth larvae. As both species matured, relative growth rates, rates of consumption, and conversion efficiencies declined.

The differences between species and the decline in rates with maturation are, at least partially, allometric (related to body size). The relationship can be expressed by the equation $y = X^b$, where y is the rate of the process and X is the size of the animal. The importance of accounting for allometry when evaluating quantitative nutritional measurements is illustrated with budworm and gypsy moth.

INTRODUCTION

This paper will examine growth of the spruce budworm Choristoneura fumiferana (Clemens), and the gypsy moth, Lymantria dispar L., each on a representative host plant. The emphasis of the study was to obtain a better understanding of the basic nutritional physiology of caterpillars, particularly in regard to changes associated with size and/or age, rather than to examine effects of food quality on caterpillar growth.

Size attained, e.g., pupal weight, is a parameter frequently used to assess the effect of host nutritional quality on insect performance. While size measurements illuminate the extent to which an insect grows on a particular food source, they do not provide information as to why a food is superior or inferior. For example, poor growth can be the result of lowered consumption due to the absence of a phagostimulant or the result of lowered food utilization due to the presence of a toxic chemical.

The quantitative nutritional approach of Waldbauer (1968) provides a method to answer such questions. This involves measuring food consumption, excretion, and assimilation and calculating utilization and efficiency rates. The effect of insect size, e.g., absolute weight, on these nutritional indices has often been overlooked by entomological researchers.

Definitions

Terminology used in this paper is patterned after that of Waldbauer (1968):

$$G = I - E - R,$$

where G = growth (biomass gained), I = food ingested (consumed), E = excretion (feces) which includes both undigested food and metabolic waste, and R = respiratory loss from metabolism.

These values, which are expressed as dry weight, can be converted to relative rates by dividing the absolute value by the elapsed time period (Δt) and the mean weight (\bar{W}) of the animal during the time period. Unfortunately, authors define mean weight according to their personal whims. Some use a simple average of the initial and final weight whereas others calculate an exponential mean based on initial and final weight. There are several methods used to do the latter. When daily or several measurements are made between the time interval, mean weight is often approximated as the sum of the individual measurements divided by the number of measurements.

Waldbauer (1964) made daily measurements and calculated mean weight by summing daily weights, after adjustment of the initial and final weights, then dividing by total number of days. This method approximates a solution by integrals. I have noted that several authors who measured only the initial and the final weight cite Waldbauer for method of calculating relative rates. What was done in these cases is unclear since Waldbauer's method is applicable only for a series of several measurements that can approximate a continuous record. Waldbauer's (1964) growth rate (GR) does not necessarily describe a true growth rate. Kogan and Cope (1974) show how this rate differs from the mean relative growth rate (\bar{RGR}) (Radford 1967) employed by general physiologists.

Herein, mean weight is defined as:

$$\bar{W}_e = W_f - W_o / \ln(W_f/W_o)$$

where W_f = body dry weight at the end of the period, and W_o = body dry weight at the start of the period. Relative rates for biomass, then, are

$$\text{Relative Consumption Rate (RCR)} = I/\bar{W}_e/\Delta t$$

$$\text{Relative Growth Rate (RGR)} = G/\bar{W}_e/\Delta t = \ln W_f - \ln W_o / \Delta t$$

Budgets and relative rates for nitrogen can be calculated in much the same manner as for dry matter biomass. It is assumed that nitrogen is not eliminated by the insect in gaseous form; hence, the nitrogen budget can be expressed as:

$$G(N) = I(N) - E(N),$$

where nitrogen gain $G(N)$ in the insect body is the difference of nitrogen ingested $I(N)$ and nitrogen excreted $E(N)$. Relative rates for nitrogen are:

$$\text{Nitrogen Accumulation Rate (NAR)} = G(N)/\bar{W}_e/\Delta t$$

$$\text{Nitrogen Consumption Rate (NCR)} = I(N)/\bar{W}_e/\Delta t$$

$$\text{Nitrogen Excretion Rate (NER)} = E(N)/\bar{W}_e/\Delta t$$

The usefulness of relative rates is that they facilitate comparison between diets, instars, and species. Food utilization indices, expressed as percentages or ratios, are also useful in making comparisons. Utilization indices used herein are:

$$\text{Ingested matter efficiency (ECI)} = \frac{G}{I} = \frac{\text{RGR}}{\text{RGR}}$$

$$\text{Nitrogen efficiency (NUE)} = \frac{G(N)}{G(N)+E(N)} = \frac{\text{NAR}}{\text{NCR}}$$

Rearing and Data Collection

Gypsy moth larvae were reared individually from neonate to pupation on excised foliage of red oak, *Quercus rubra*. Foliage was changed at 48-hr intervals and kept turgid by placing the leaf stem or twig in a vial of water. Larvae were placed on the foliage about one week after budbreak and maintained at temperatures that approximated outdoor weekly mean temperatures. Eight to twelve of the larvae were sacrificed at the beginning of each instar just after hatch or the molt before any feeding occurred. The dry weight of the insect body including the newly molted larval skin, and the feces produced during the instar were measured. Standard micro-Kjeldahl procedure was used to find the nitrogen content of larvae and feces and the percent nitrogen of freeze-dried subsamples of the foliage provided the larvae at each feeding. Nitrogen ingestion was calculated as the sum of $G(N)$ and $E(N)$. Dry matter ingestion was calculated as $I(N)/N/\text{mg foliage}$.

Spruce budworm larvae were reared on artificial diet until mid third instar at which time they were placed individually on a single terminal bud of balsam fir, *Abies balsamea* that had just shed the scale cap. They were maintained outdoors in a weather station box at ambient temperature. Humidity in the 28 ml plastic rearing container was at or near 100% RH. Larvae were divided into two groups: those that were sacrificed periodically to obtain dry weight and nitrogen content as percent of wet weight, and the experimental group reared to pupation. For the latter group, foliage was changed, frass separated from foliage and larval wet weight measured at 48-hr intervals. Larval dry weight biomass was estimated from the wet weight times the dry/wet weight ratios of larvae of corresponding size. This value was reduced 20% to account for gut contents except for larvae ready to enter the prepupa stage. Dry weight or N consumption of foliage was estimated by (1) counting number of needles damaged (completely or

partially consumed) and measuring length of uneaten portions and (2) determining mean length ($\bar{x}L$), dry weight, and nitrogen content of undamaged needles from the same twig which was used to calculate needles eaten as:

$$\frac{((\# \text{ damaged needles}) \times (\bar{x}L)) - (\text{total uneaten length})}{\text{mean length}}$$

Thus:

I = needles eaten \times mean wt/needle

$I(N)$ = needles eaten \times mean N/needle

Results and Discussion

Table 1 compares spruce budworm and gypsy moth weight, development time, fecundity and conversion efficiencies. For the sake of convenience and brevity, only the data for females are presented throughout the paper. The budworm increased body weight about 2000-fold and the gypsy moth nearly 3000-fold; but the gypsy moth took 50% longer to complete development. In effect, the gypsy moth achieved a greater absolute percentage increase in size, but did so at a slower rate of growth (RGR). The gypsy moth also fed less efficiently than the budworm both in terms of dry matter and nitrogen. This may have contributed to the lower RGR of the gypsy moth however; as will be pointed out the difference in rate could also be explained by size differences.

The RGR, ECI, and NUE values, as presented in Table 1, represent averages for the entire larval period (*L. dispar*) or for the third instar until pupation (*C. fumiferana*). It is common practice to make measurements across instar or the entire larval stage and to express the results as a constant value independent of absolute body weight. This is an arbitrary simplification that fosters the idea that rate of growth and food conversion efficiency remain unchanged as the larva grows. In reality, such rates and indices are not constant as the animal grows but change, usually in a systematic manner with time or the weight of the insect. It would seem, therefore, that a parameter which depicts change in rate (=slope) would be as useful as mean relative rate.

Table 1. Bionomic data for female larvae

Insect Host	<i>C. fumiferana</i> Fir	<i>L. dispar</i> Red Oak
Initial dry weight (ug)	18	140
Pupal dry weight (mg)	30	400
Development time (days)	30	48
Relative growth rate (ug/mg/°day)	15.6	11.1
Biomass conversion efficiency (%)	9.1	6.6
Nitrogen utilization efficiency (%)	40	30

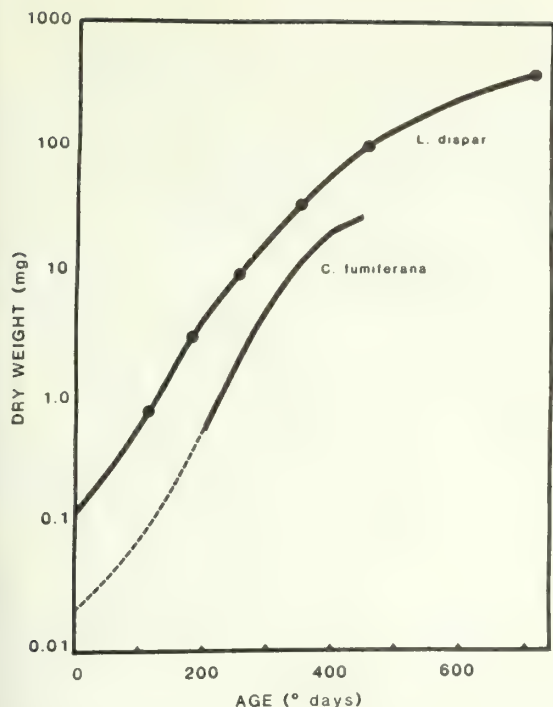


Figure 1. *L. dispar* and *C. fumiferana* growth against time. Measurements for *L. dispar* were made at each instar molt; for *C. fumiferana* every 2 days beginning at 200 degree days, the dashed line is an extrapolation.

It is also common practice to plot against time the log weight of the developing organism (Fig. 1). An easy and frequently used method to mathematically describe such growth is to regress the logarithm of the weight on time. This type of regression is appropriate if growth was exponential; i.e., weight increases at a constantly increasing rate until death or metamorphosis interrupts the process. If the growth of the two caterpillars was exponential, the data sets plotted on a log linear scale, as in Figure 1, would produce a straight line. The growth curves though are clearly sigmoid; i.e., the weight increases exponentially but with a rate of increase that changes with time. Curves used to describe this type of growth are, among others, the power, Gompertz, logistic, and Bertalanffy (Kaufman 1981).

The Bertalanffy equation has been used to describe the growth of plants, fish, mammals, and humans. It can be written as:

$$dW/dt = nW^a - kW \quad (1)$$

where W = weight, t = time and a , k , and n are parameters.

A closed form solution of this equation is:

$$W = \left[\frac{n}{k} - \left(\frac{n}{k} - W_0^{(1-a)t} \right) e^{-k(1-a)t} \right]^{1/(1-a)}$$

where W_0 = weight at time, $t=0$. Needless to say, fitting this and other nonlinear models to data requires knowledge of calculus and matrix algebra and a computer programmed to do a nonlinear least-squares analysis. Such process is beyond many while to others proposing plausible equations and seeking "the" formula that most closely approximates the experimental data is great mental sport. The goal however should not be to achieve high statistical fit via complex equations but to describe and use data in a manner that facilitates evaluation of effects of substrate and environment on the growth process.

Graphical plots are a convenient, straightforward method that allows one to describe changes in growth rate as a function of size.

Figure 2 shows that body size and RGR of *L. dispar* and *C. fumiferana* are allometric functions. With both species, the log of RGR more or less decreased in direct proportion to the log of the weight. Although the overall RGR of the budworm was higher than that of the gypsy moth, it was more sensitive to size and decreased at a faster rate as the larvae grew.

The initial value for *L. dispar* represents the first larval stadium and may underestimate RGR. *L. dispar* neonates normally spend the first 24-48 hours wandering and not feeding; a period of dispersal. To account for this, the time interval for the stadium was shortened 17 degree-days which may have been insufficient. On the other hand, the first instar RGR may actually be lower since the larva must replenish the moisture and energy expended during the nonfeeding interval before a net increase can occur.

The greater fluctuation of the *C. fumiferana* data about the regression line reflects the higher variability in measurements for this species. Standard errors of budworm larval weight and consumption ranged from 10-20% of the mean whereas gypsy moth standard errors were always less than 10% of mean values.

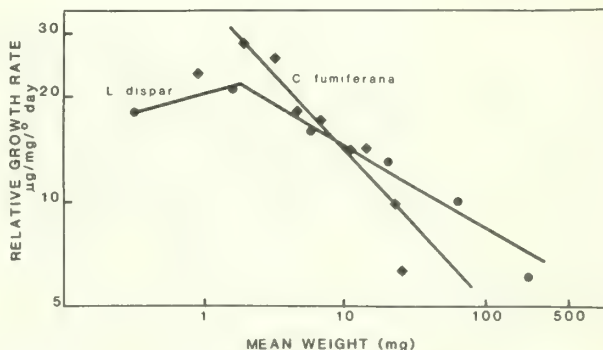


Figure 2. Relative growth rate (RGR) of *L. dispar* and *C. fumiferana* against mean weight (\bar{W}_e).

The relationship between metabolic rate and absolute body size is one of the classical topics of comparative physiology. That the normal or basal metabolic rate of plants and homeothermic and poikilothermic animals is inversely related to body size; i.e., smaller organisms have higher metabolic rates, is something learned by introductory biology students (Keeton 1972). This relationship can be approximated by allometric formula (Huxley 1932):

$$M = bW^{\alpha} \quad (2)$$

where M = metabolic rate per unit of time, W = body weight, and α and b are constants. For weight-specific metabolic rates, the equation becomes:

$$\frac{M}{W} = b W^{\alpha-1} \quad (3)$$

On a log-log graphical plot, an empirical data set that follows this function would afford a straight line regression, the slope of which indicates α . If $\alpha = 2/3$, then the surface rule is being followed; i.e., the change in rate decreases in proportion to the change of surface area. If the slope is 45° , $\alpha = 1$, then change in rate is directly proportional to the change in weight. Bertalanffy (1957) has proposed that metabolic rates of most animals are proportional either to surface area, to weight, or, more rarely, lie between these two types. Brody (1945) however, indicated that basal metabolic rate varies at the $3/4$ power of weight. Most laboratory measurements are close to this value (Fenchel 1974).

It is not unreasonable to assume that rules similar to those regarding the size dependency of metabolic rates would extend to growth rates. After all, is not growth in its simplest terms but the product of anabolism minus catabolism? Adolph (1949) showed that, at least in first approximation, the rate of all physiological processes can be expressed as allometric formulae. Thus, change in body weight can be expressed as a function of the difference between building up and breaking down; i.e.:

$$dW/dt = nW^a - kW^b$$

This is similar to the Bertalanffy equation except for the addition of parameter b . Bertalanffy (1957) in developing his equation argued that catabolism is directly proportional to weight and since the basic equation is rather insensitive to minor deviations in b , it can be regarded as equal to one. The exponent a then more or less depicts the relationship of growth rate to body weight.

Less predictable is the effect of body size on food consumption rates and food conversion efficiencies. Food consumption would be expected to be proportional to body weight if the insect simply feeds to repletion once or twice daily. In this case, digestive efficiency would likely decrease with increasing body size, since gut surface area decreases at about $2/3$ power of gut volume. Conversely, if digestive rate rather than gut volume delimits the rate of food consumption, one would expect digestive

efficiency to be rather independent of body size and consumption to be more proportional to surface area than to body volume. Food conversion, however, is not just digestion but also intermediary metabolism plus several complex and intertwined physiological and metabolic processes and thus it is difficult to predict what type of model would fit. The final net result however is measurable and can be tested for size dependency.

Figure 3 plots logarithmically RGR as well as several other nutritional indices. The regression lines are fitted by eye and approximate. The plot is intended only to illustrate the relationship of the general trend of the indices to each other.

With *L. dispar* (Fig. 3a), RGR followed the same pattern as RGR except that RGR decreased at a slower rate as size increased. Consequently, ECI (Fig. 3c) decreased. The nitrogen budget (Fig. 3b) followed a similar pattern. NAR decreased at a steeper rate than NCR; hence, NUE (Fig. 3c) also decreased as size increased. Note that the NER changed much less with weight than either NAR or NCR. Both NUE and ECI had about the same slope; an indication that they were not affected differentially.

The *C. fumiferana* data are more complex. They are also less precise; hence, interpretation must be taken lightly. In this case, RCR decreased but then began to increase as pupation neared while RGR changed at a constant rate (Fig. 3d). NCR exhibited a similar pattern even though NAR decreased continuously as size increased (Fig. 3e). NER was apparently little affected by larval size. Since RCR and NAR decreased at a decelerating rate and rate of decrease of RGR and NER remained constant, ECI and NUE decreased at an accelerating rate (Fig. 3f).

My starting hypothesis was that since RGR is affected by weight, RCR and ECI would also be influenced by weight since $RGR = RCR \times ECI$. Indeed, a general pattern was observed where growth, accumulation, and efficiency decreased as body size increased. However, each index had a different slope which indicates independent influence and/or compensation mechanisms.

Rate/efficiency interactions involve the complex area of feedback and homeostasis and is an area largely unexplored by insect physiologists. Slansky and Feeny (1977) proposed that rate of growth or accumulation is held stable, maximal, by compensatory changes in consumption and efficiency. Their data supported the hypothesis of Odum and Pinkerton (1955) that power and efficiency cannot be maximized simultaneously and that power (i.e., assimilation rate) would be selected for.

An examination of the regression coefficient of the indices (Table 2) for *L. dispar* not only supports the thesis that power or accumulation rate is stabilized at a high rate but also offers an explanation why efficiency decreases as size increases. The reason for suggesting that *L. dispar* RGR and NAR are maximal is that the constant of proportionality, $a-1$, was very close to the $3/4$ power rule for metabolic rate. In other words, the caterpillar's accumulation of biomass and nitrogen changed at the theoretical, expected rate despite changes in food supply. (Effect of food will be discussed later.)

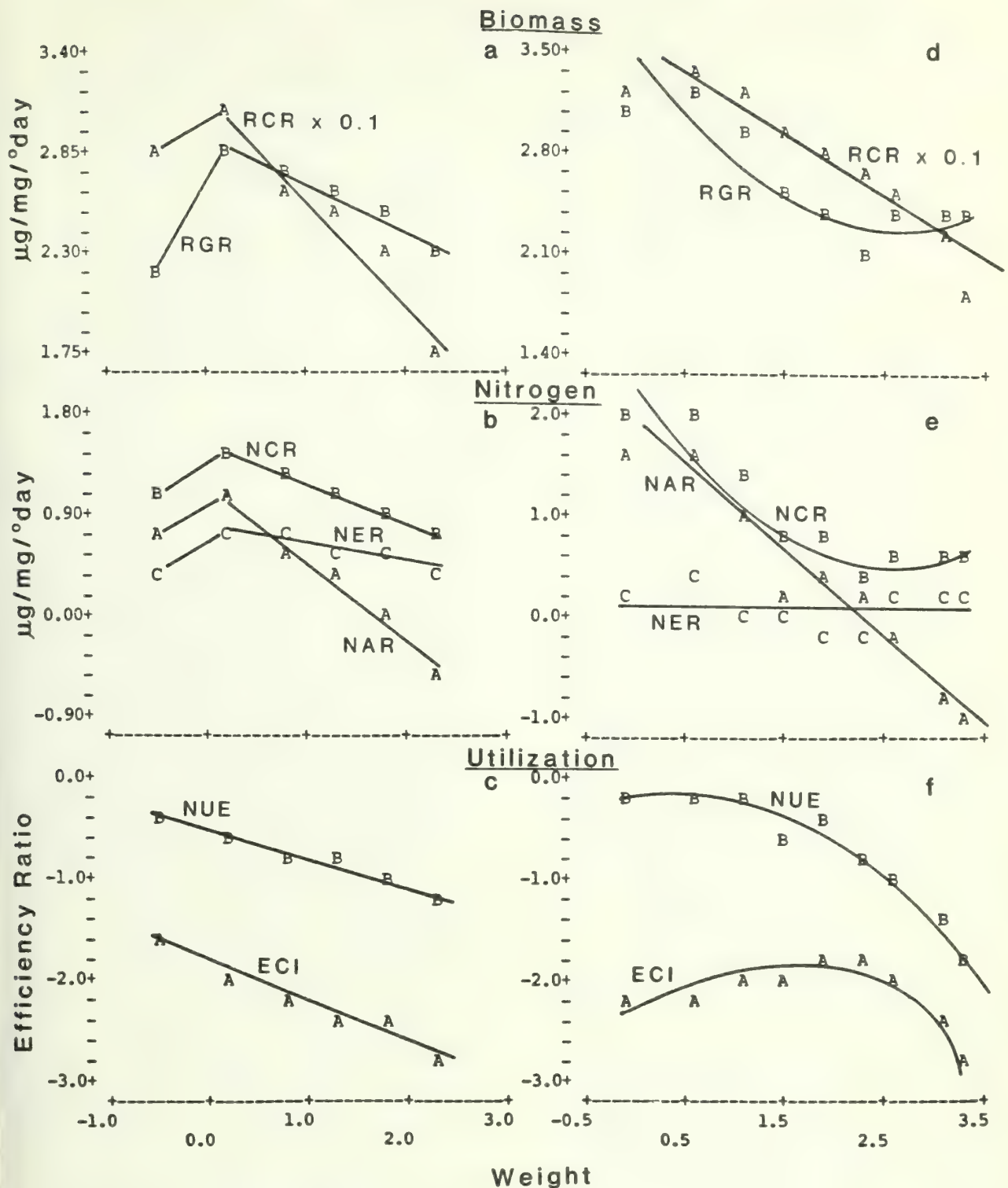


Figure 3. Weight dependency of nutritional indices. Values have been converted to natural logarithms. (See Definitions section for abbreviations.)

Table 2. Regression equations and coefficients of determination of nutritional indices on log \bar{W}_e . The equations have the form: $\log(\text{index}) = a \log \bar{W}_e + \log b$. (Index units = $\mu\text{g}/\text{mg}/^\circ\text{day}$, weight = mg).

Index	<u>L. dispar</u>			<u>C. fumiferana</u>		
	b	a-1	r ²	b	a-1	r ²
RGR	182.6	0.90	0.94	236.1	0.69	0.71
RGR	25.2	0.75	0.97	31.4	0.62	0.81
NCR	4.7	0.85	0.99	6.6	0.53	0.76
NAR	2.8	0.73	0.96	6.2	0.18	0.93
NER	2.1	0.93	0.97	0.5	-0.71	0.38

Consumption and excretion also seem to be following ideal case models. These indices are fairly close to one and hence more directly proportional to volume (= weight) compared to accumulation where direct proportionality is closer with surface area ($A = V^{2/3}$). Since gut volume is roughly proportional to body volume (= weight), then a proportionality constant for RGR of near zero ($0.9 - 1 = -0.1$) indicates the insect eats to repletion. Assimilation of the food however proceeds only at the $3/4$ power of the rate of intake; hence, assimilation efficiency decreases as intake increases. This scenario implies little feedback control over feeding rate, the insect simply eats until it is full if food is available and palatable.

The data suggest an intriguing, alternative scenario. Catabolism is also weight proportional (cf. L. dispar NER) and responds more to weight change than anabolism (Bertalanffy 1957). This fact also can explain size related decrease in efficiency. Further, if catabolism and/or elimination of metabolic waste were rate limiting, it, through feedback, could control feeding rate. An excess of nonutilizable metabolites that must be eliminated would depress feeding rates. Better assimilation efficiency would result in faster growth not only from the increased conversion, but also from an increase in consumption the production of less wastes would afford.

These remarks about rate/efficiency interactions are pure speculation. Its purpose is more to illustrate the caution required and the difficulty in relating indices to performance or to cause and effect.

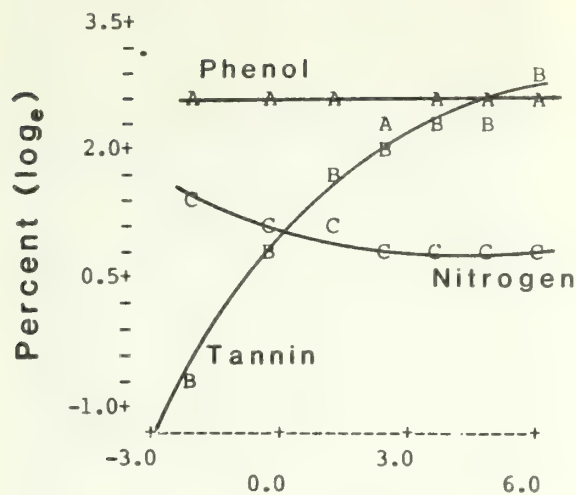
The spruce budworm data in Table 2 were ignored in the preceding discussion because the data apparently illustrate effect of substrate more than ontogeny. The budworm proportionality constants were lower than expected and suggest that phenological changes in the fir foliage placed increasing stress on the budworm as it matured. On the other hand, the gypsy moth data seem to reflect mainly a scaling effect. One would need to suppose that young oak foliage was relatively less suitable than older foliage or that the lower early season temperatures were more favorable in order to account for a phenological effect on the gypsy moth constants.

To illustrate phenologic relationships between foliar chemistry and the indices, I have plotted some of my unpublished foliar analyses on logarithmic axes with the corresponding mean larval weight substituted for sample date on the axis of the abscissas (Fig. 4). Significant correlations of chemical levels with nutritional indices are almost a foregone conclusion simply because the indices decline with size (time) and most of the chemicals either increase or decrease in concentration with time. Because of the overbearing effect of allometry, few of these correlations can be rationalized. For example, condensed tannin in oak leaves increased as the leaves matured whereas in fir tannin decreased after budbreak. In the first case, the correlation coefficient with RGR is -0.96 and in the second, 0.99 . Total phenol in oak is obviously poorly correlated with RGR, but it cannot be ruled out that total phenol was without influence if the change in RGR is mainly ontological.

The situation with nitrogen seems more informative. Budworm RGR and NCR were strongly correlated, 0.96 and 0.99 , respectively, with foliar nitrogen. Budworm development was rapid and closely synchronized with foliar expansion. The larvae were in 3rd instar at budbreak and pupation occurred as the foliage became fully expanded and nitrogen level stabilized. With oak, leaf expansion was completed and nitrogen level stabilized when the gypsy moth larvae were about half grown. In this case, correlations of nitrogen with RGR and NCR were less, about 0.7 .

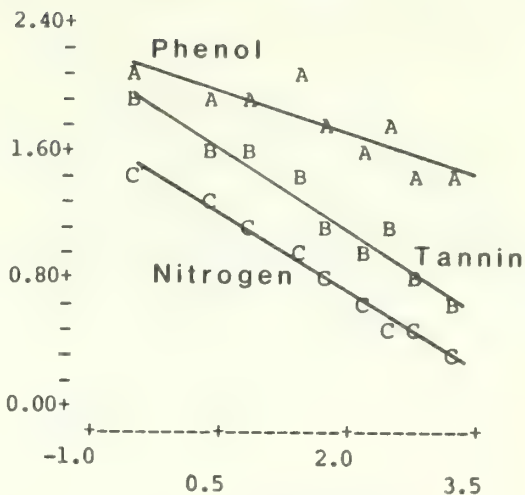
Nitrogen in mature fir foliage may have been limiting to budworm since it was below 1.5% . Oak, by contrast, had 2.3% N in mature foliage. It would seem to be advantageous for the budworm to complete development before the foliage matures. Both its habit of attacking foliage before buds break and its small size may be adaptations that aid this. Decline in growth rates with increasing size occurs also among species, i.e., small animal species tend to have higher RGR (Schmidt-Nielsen 1975). McNab (1978) stated that herbivores of equal size feeding on woody foliage have significantly lower metabolic rates than those feeding on richer plant tissues. The budworm gypsy moth comparisons do not support this. (See Mattson 1980 for more on body size.)

RED OAK



L. dispar

BALSAM FIR



C. fumiferana

Lar al Weight (\log_e mg)

Figure 4. Seasonal change in concentration of foliar chemicals in relation to larval weight at time of sampling. Values have been converted to natural logarithms.

Gypsy moth is a rather large caterpillar with a rather long development time for a ring-feeding arborivore. Speed may have been sacrificed to efficiency (Fig. 5). Budworm by contrast had higher NUE on spruce where growth was less. The plants that supported poor budworm growth also had lower foliar nitrogen levels (Montgomery, unpublished). This observation complements the data for developing larvae (Figs. 3 and 4) where, as nitrogen became in apparent nutritional supply, NUE decreased more than expected while NAR was maintained. Both host and development data for budworm support the thesis of Odum and Pinkerton (1955) that efficiency is

of lesser importance than rate. It should be clarified that although changes in RGR due to size applies to different sized individuals, species, etc., there is no evidence (see Banse 1979) that the weight (= age) dependent efficiency that occurs in a growing individual applies to individuals of different size. Thus, the size/efficiency relationship of budworm in Figure 5 may or may not be allometric.

Although firm statements about the weight dependency of nutritional indices cannot be made, that such effects may exist is sufficient reason to consider the role of allometry when interpreting quantitative nutritional data.

Acknowledgement

Gratitude is extended to David Mikus for making the arduous budworm measurements and for the graphics.

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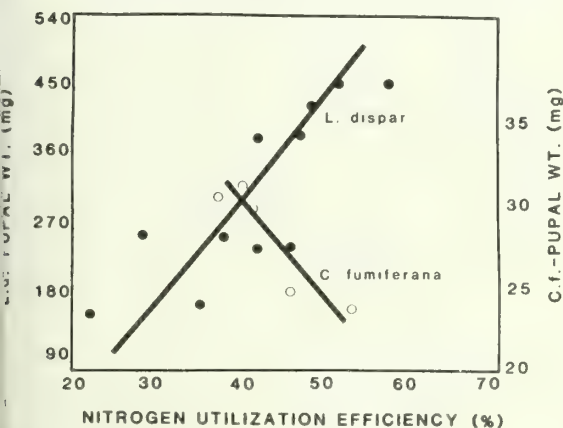


Figure 5. Mean nitrogen utilization efficiency against mean female pupal weight for *L. dispar* (L.d.) on eleven different host species and for *C. fumiferana* on white spruce hosts differing in age and vigor (Montgomery, unpublished).

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Many of the papers presented discussed foliage chemistry and/or the response of caterpillars to dietary chemicals. The concluding papers, one by Houston on characteristics of trees resistant and susceptible to defoliation by gypsy moth, and the other by Witter et al. on management implications of budworm/host interactions, do not discuss foliage chemicals or foliage quality per se. Instead, they focus on traditional site classification systems. More than anything, this is indicative of where the "state-of-the-art" is and the gaps in knowledge that future research should fill.

Forests have traditionally been classified on the basis of physical and phytosociological characteristics such as soil, slope, species composition, stocking density, and tree age. Because of their familiarity to the forest manager and their relative ease of measurement, they are the characters currently being incorporated into the classification schemes. Such entities are being removed from the actual cause-effect relationship. They act on the physiology and growth habit of the host tree (the "room and board" referred to in the paper by Wallner) which in turn influences pest insect populations. The quality of the "board", at its lowest level, is determined by the chemicals used in the forest and anything that affects the ability of the insect to access or utilize them.

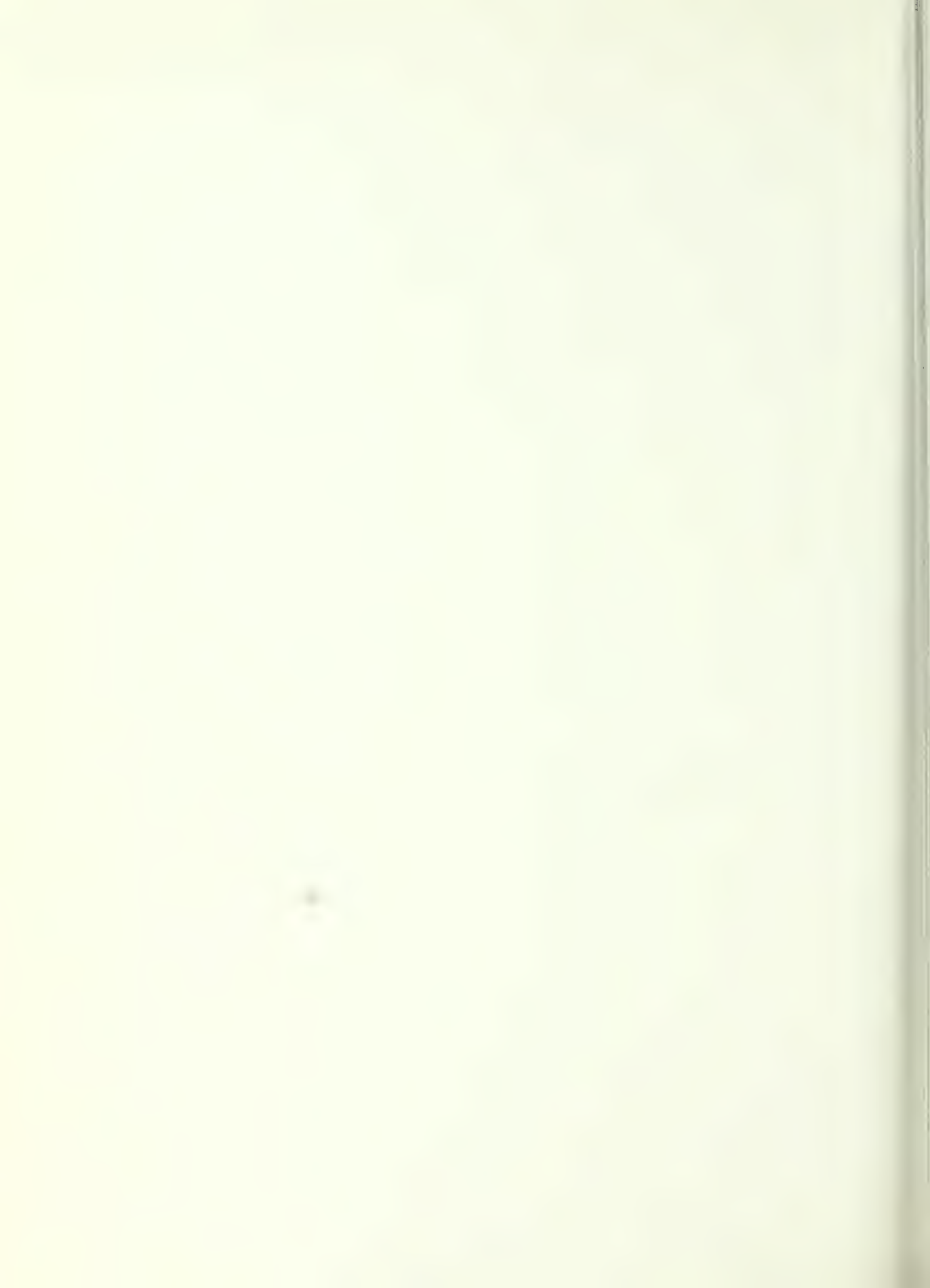
Research at this level may seem distant to practical payoffs. The papers presented indicate the progress and challenges of such work. In the introductory chapter by Talerico cited that the relationship between budworm growth and natural variation in foliar components had not been previously demonstrated. Papers given by Wagner, Blake, Montgomery, Mattson et al., and Smith et al., noted a positive correlation between budworm pupal or adult weight and concentration of foliar nitrogen. The importance of nitrogen did not extend to the gypsy moth. Howitz found little correlation between foliar N levels and gypsy moth host preferences. Montgomery reported a similar situation with pupal weight. The latter author did report, however, that nitrogen utilization efficiency was highly correlated with gypsy moth pupal weight. Apparently something, perhaps tannins, inhibited utilization of the foliar nitrogen. Of the several papers that presented data on tannin or phenolic foliar levels, none reported strong evidence of a negative effect on budworm or gypsy moth. Schultz and Baldwin explained, however, that it may not be the "mean" level of a secondary chemical in the tree, but the induction or increase in concentration in response to insect attack that is important. Thus, foliage quality should not be considered as static, but dynamic and variable, not only in time, but also in space. This presents sampling problems not only to the insect, but also to the researcher. The models presented by Valentine and Fleming indicated that lowering of foliage quality may not

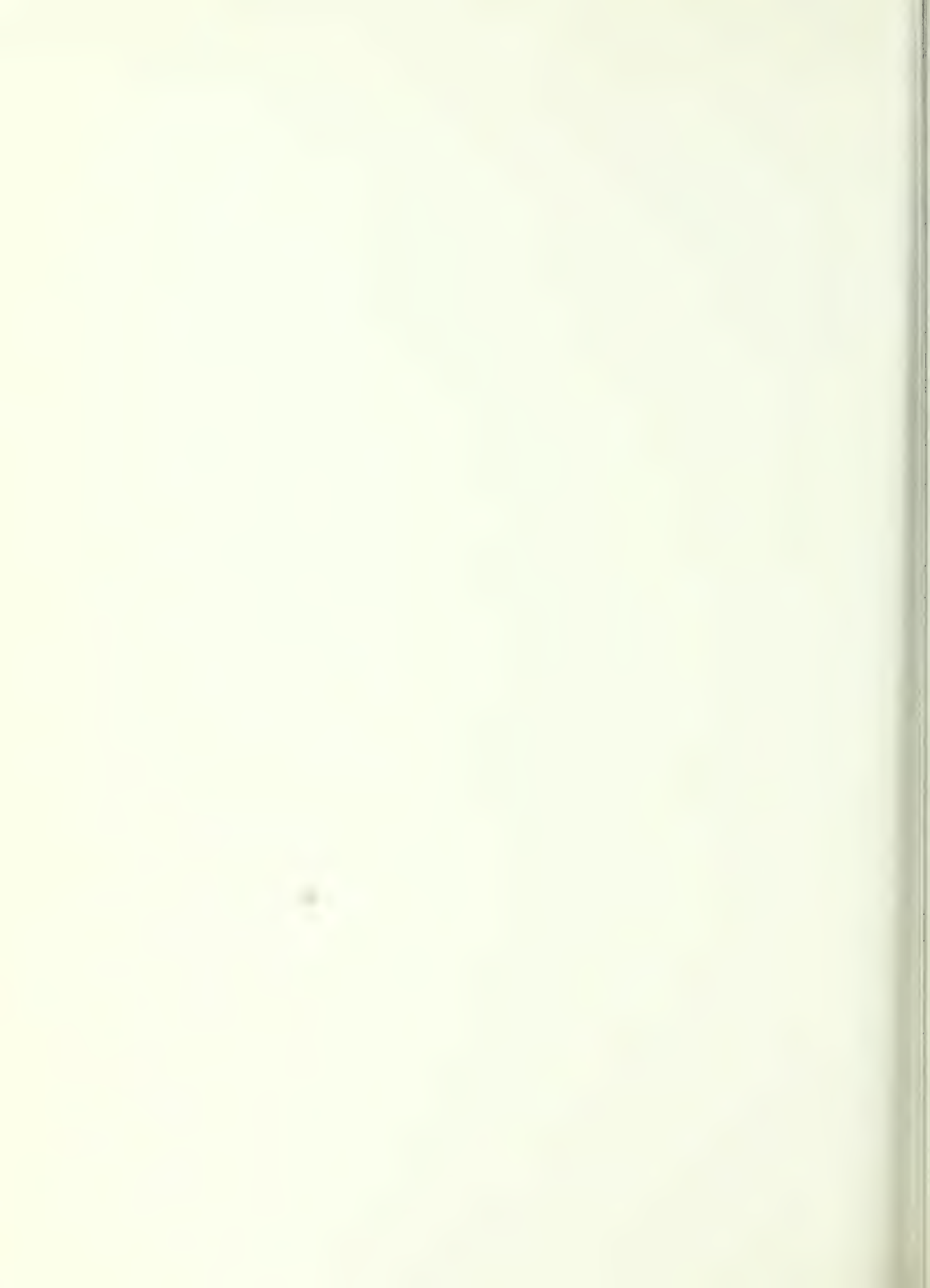
necessarily be beneficial from a pest management standpoint for populations may be prolonged at high levels instead of crashing because of starvation.

I must chide myself as well as this symposium for focusing excessively on foliage chemistry. Many other aspects of the host insect interaction such as Shepard's paper on bud phenology were also discussed. But perhaps the greatest imbalance was the focus on identifying mechanisms responsible for host suitability without documenting their action in the field under natural conditions. The second paragraph of the paper by DeHayes comments well on this.

August 1983 Michael E. Montgomery, Hamden, CT







Talerico, Robert L.; Montgomery, Michael, Tech. Coords.
Proceedings, forest defoliator--host interactions: A
comparison between gypsy moth and spruce budworms; 1983 April
5-7; New Haven, CT. Gen. Tech. Rep. NE-85. Broomall, PA:
U.S. Department of Agriculture, Forest Service, Northeastern
Forest Experiment Station; 1983. 141 p.

Fosters communication between researchers with active research
projects designed to understand the relationships between the
host plant and forest defoliator feeding behavior, growth,
and reproduction.

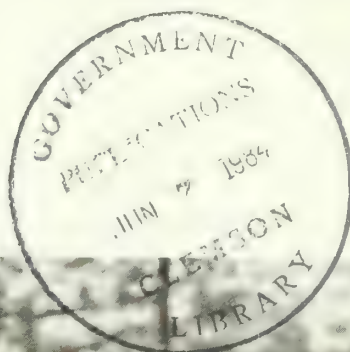
Headquarters of the Northeastern Forest Experiment Station are in Broomall, Pa. Field laboratories are maintained at:

- **Amherst, Massachusetts, in cooperation with the University of Massachusetts.**
 - **Berea, Kentucky, in cooperation with Berea College.**
 - **Burlington, Vermont, in cooperation with the University of Vermont.**
 - **Delaware, Ohio.**
 - **Durham, New Hampshire, in cooperation with the University of New Hampshire.**
 - **Hamden, Connecticut, in cooperation with Yale University.**
 - **Morgantown, West Virginia, in cooperation with West Virginia University, Morgantown.**
 - **Orono, Maine, in cooperation with the University of Maine, Orono.**
 - **Parsons, West Virginia.**
 - **Princeton, West Virginia.**
 - **Syracuse, New York, in cooperation with the State University of New York College of Environmental Sciences and Forestry at Syracuse University, Syracuse.**
 - **University Park, Pennsylvania, in cooperation with the Pennsylvania State University.**
 - **Warren, Pennsylvania.**
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Photographic Techniques for Monitoring Resource Change at Backcountry Sites

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Abstract

Resource change can be monitored by photographic methods. The question resource managers must ask is whether and how a photographic monitoring program fits with: (1) existing monitoring programs; (2) data requirements; (3) available equipment and funds; (4) personnel deployment; and (5) visitor education or personnel training needs.

The microsite techniques described in this report are generally the more expensive, requiring more time or specialized equipment in the field or lab than the macrosite techniques. The data obtained are detailed and, in some cases, quantifiable enough for research purposes. Quadrat photography could supplant a field quadrat analysis program. Trail mosaics could provide excellent vegetation records to accompany trail profiles obtained from nonphotographic trail transect monitoring programs. Stereo (or mono) photographic trail transects, although generally more expensive than field measured transects, are reasonable substitutes where it is essential that data be verifiable.

Macrosite techniques are less likely to provide research data, but are very useful for qualitative assessments. Panoramas can be produced in the course of normal inventory routines to provide supplemental information. They are more effective, however, if obtained through a carefully planned program of photographing each site at nearly exact 5-year intervals, but the logistics might be prohibitive. The monoscopic perspective grid technique can provide some measurable data, but it has limited applicability, and cannot be relied on for comprehensive surveys of site conditions.

The principal advantage of any photographic monitoring system is the visual record it provides. The viability of these techniques will, therefore, always depend on how much value is attached to: (1) the impact of pictorial display of resource change versus written description; (2) the convenience of laboratory or office (rather than field) data analysis; (3) the reproducibility of raw data; and (4) the reduction of subjectivity by personnel.

Acknowledgements

Materials for this report were drawn from many unpublished sources; consequently, the literature citations do not adequately reflect all of the contributors. The following persons and organizations deserve commendation: Anne Whitney and Jane McBride for the design and application of the quadropod technique; Laurence Van Meter for the development of the trail mosaic technique; Steve Rice, Harry Peet, and the Green Mountain Club for information gleaned from an ongoing 6-year photographic campsite monitoring program; Robert Vinton for the development of the perspective grid technique; Harriet Plumley for the coordination of this report; and Raymond Leonard for the encouragement and counsel of the staff of the Northeastern Forest Experiment Station's Backcountry Recreation Research Project in their search for better ways to monitor recreation resources.

Foreword

This report has been prepared under the auspices of the USDA Forest Service and the Appalachian Trail Conference to bring together assorted information on photographic techniques for monitoring resource change at wildland recreation sites. For the most part, the techniques were originally devised to gather research data, but some are practical enough to be useful management tools as well.

Introduction

Reasons for Resource Monitoring

A well-conceived resource monitoring program is essential to sound management planning. Research data and site inventories collected over time provide vital information about what, where, why, and how fast changes are occurring in the physical, biological, and aesthetic conditions of the resource. For wildland recreation managers, such information affects decisions concerning: (1) where to develop and how to assign priorities to maintenance programs; (2) what levels of funding are necessary to protect or improve the resource; (3) which plant species or ground conditions are the most fragile and should be monitored the most closely; (4) where visitor use patterns or types of use should be changed to reduce resource deterioration; and (5) how effective certain management programs have been (e.g. campsite reclamation). A good monitoring program, therefore, provides a record of changes in conditions of the resource, and documents the effects of certain management policies and actions.

Resource Monitoring Systems

Collecting information on wildland recreation conditions is expensive because access is limited and the resources extensive. To be cost-effective, monitoring programs must be systematic. The system must be designed to achieve a specific set of objectives; produce detailed and replicable records by easy-to-use methods; and permit ready retrieval of those records for comparisons of sites over time (Hendee et al. 1978).

Two exemplary systems currently in use to inventory and monitor backcountry campsites are Code-a-site (Hendee et al. 1976), used by the U.S. Forest Service, and the Human Impact Inventory (Moorhead and Schreiner 1976) used by the National Park Service. Both systems require field personnel to assess conditions at individual campsites. The information is recorded on cards which have "needle sorting" holes along the margin. The cards are preprinted with the desired information organized into categories around the perimeter. The needle-sorting process permits quick and easy comparisons between campsites for inventory purposes. Cards for individual sites can also be compared over time to monitor changes.

Currently used methods of monitoring trail (as opposed to campsite) conditions are less sophisticated in information storage and retrieval. Some backcountry managers and researchers collect data systematically by running a calibrated wheel along the trail and reporting conditions at standard intervals from a specified starting point (Leonard and Whitney 1977).

The Role of Photography

Photography can also be used systematically to provide a permanent record of site conditions for comparisons over time. A photographic monitoring system should enhance (not necessarily replace) the nonphotographic systems previously discussed. A visual record of campsites and trail locations can be advantageous for a number of reasons.

Photography can reduce subjectivity in recording site conditions. With campsite inventory systems, the accuracy and reliability of the information obtained depend on the strength of the criteria set forth in the coding instructions (Hendee et al. 1976), how closely the individual collecting the information follows the criteria in making his or her judgment, and the training and experience the observer has had. Photographs can be used to establish codebook criteria by providing characteristic examples of the different conditions that require classification. In addition, photographs can provide a means of validating field assessments by allowing more than one qualified observer to view the conditions of the area at a single point in time. These attributes are particularly important when personnel changes increase the variability of subjective bias.

Photography can, in some cases, reduce field costs. Where visual assessments are the primary source of information, less experienced field personnel can easily be trained to take representative photographs so that professional staff can perform the necessary analyses at their convenience in the office or laboratory.

Photography can be used as an educational tool. New personnel can be shown the past and present conditions of the resource quickly. The successes or failures of preventive maintenance, rehabilitation, or site hardening programs can be documented by photographic records. Interpretive programs designed to educate visitors on the impacts of their use of the resource, or the reasons behind certain regulations, can benefit from photographs obtained from monitoring programs.

Photographic monitoring techniques can give management information useful for decision making, but their use should be considered in the context of the types of data required and how field personnel are normally deployed. Photography cannot meet all data requirements; for example, many quantitative assessments such as soil analyses cannot be obtained from photographs. On the other hand, photographs are excellent for evaluating aesthetic conditions (Buhyoff and Leuschner 1978), and ecological trends (Gruell 1980). Photographic techniques for monitoring require more attention to timing than some nonphotographic techniques, since duplicating a photograph at the same time of day and near the same day of the year is often a requisite for usable results. This may be more difficult for field personnel to do in the course of normal routines than using Code-a-site or similar inventory/monitoring systems.

Photopoint Photography

The techniques detailed in this report require a referenced and relocatable camera position from which photographs can be taken periodically for comparison. When done properly, "photopoint" photography provides more accurate and useful qualitative data than simple "snapshot" photography. In addition, some degree of quantifiable information can often be obtained without sophisticated photogrammetric techniques or equipment. Since establishing a photopoint is part of the field methodology for many of the techniques to follow, the procedure is set forth here.

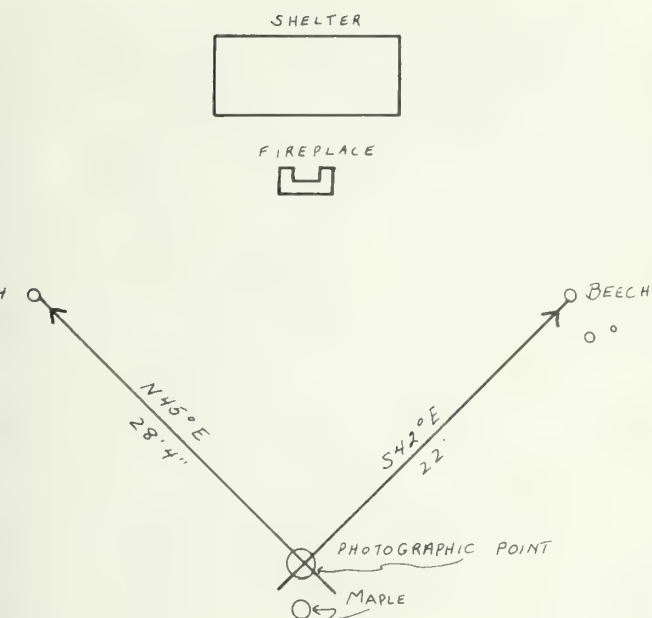
Field procedure. The first step in establishing a photopoint is to analyze the subject area carefully. Select a camera position that provides the most advantageous perspective (with the available equipment) of the expected change. Photographers on successive photo missions may feel compelled to move the camera point slightly to achieve what they feel is a better coverage of the subject. This might result in a loss of information, which could be avoided by properly anticipating what

coverage will be necessary as changes occur over time. Documenting the reason for the camera placement when it is not immediately evident may avoid costly changes.

Once a location for the photopoint has been determined, a physical marker is required. Permanent landmarks such as boulders or other large objects should be taken advantage of when possible (Magill and Twiss 1965). Where landmarks such as these are not available, some kind of stake should be driven flush with the ground. Size, weight, and durability are limiting factors. Wood is light, but may deteriorate faster than desired. Objects as small as nails can be used with magnets attached to permit relocation with a compass or metal detector. Frost heaving can be a problem for small markers such as nails; large spikes may be more appropriate where the ground freezes. Any marker should be as inconspicuous as possible to avoid vandalism.

Referencing the photopoint is the next step. Two nearby permanent objects can be used as references, but three are better. Trees are good references and may be marked with numbered aluminum tags. (Note: Tags are not appropriate in designated wilderness.) Identification tag numbers should be recorded along with the bearing and distance from each tree to the photopoint. Sketch maps should be made showing the azimuth from the reference object to the photopoint, the dbh and species of witness trees and the general object area in relation to trailheads, shelters, access roads, etc. (Figure 1). An altimeter reading and slope aspect indication should also help locate the photopoint on topographic maps. A photograph of the area and camera setup is also useful for relocation.

If different cameras are used for successive photos from the same point, they should at least be of the same format and use the same length lens. Film of the same type, speed, and spectral sensitivity should be used when possible. A change from black and white to color film can be made with less loss of information if a set of black and white



FILM: Kodak Tri-x, 400 ASA.
 Lens center 4' above ground.
 Canon FTB, 28mm Canon FD lens.
 F-stop, speed f-5.6 @ 1/30.
 DECLINATION: 15½°W

Figure 1.—Sketch map showing the location of the photopoint.

Quadrat Photography

Photos are also made from the color film or slides for the first year of comparison. The time of day should be selected as closely as possible to avoid shadows in different positions. Photos should also be taken during the same time of year (the size of the "flow" of duplication days will vary according to the needs of the study). Making copies of the original photos in the field can facilitate accurate reproduction.

The quadrat photography technique described here was developed at the Northeastern Forest Experiment Station in Durham, New Hampshire, for use in controlled experiments to study the impacts of trampling and group camping activities on certain designated areas. Photographs of quadrats were analyzed to determine the effects of such impacts on surface soil and forest litter conditions, vegetation survival, and species composition.

Equipment. The principal piece of equipment is a quadropod whose four legs attach to a 1 by 1½ meter quadrat frame. The whole unit can be disassembled to be moved. The quadropod keeps the film plane a specified distance from and parallel to the ground. The rectangular shape of the quadrat makes a 35 mm camera most practical. A lens of 35 mm focal length is necessary to include the full quadrat in the frame with the quadrat size and camera-to-subject distance prescribed for this particular quadropod (Figure 2).

Other equipment includes an electronic flash unit, some opaque cloth and color film. A flash unit with sufficient power to provide full even coverage of the quadrat should be aimed directly at the ground plane to provide uniform lighting with minimal shadow. On bright, sunny days, the cloth should be used to shade the quadrat to keep the lighting uniform. Color film is preferable to black and white for differentiating between such things as live seedlings and forest litter. Color infrared may provide even greater differentiation in some instances. Slides are preferable to prints because they can more easily and inexpensively be enlarged by projection. If color slides are used, some sort of rear projection device is valuable. The Kodak Ektagraphics Series of tabletop rear projectors provide useful image sizes (from 35 mm slides) and a smooth hard viewing surface on which delineations can be drawn on acetate overlays.¹

¹The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture or the Forest Service for any product or service to the exclusion of others that may be suitable.



Figure 2.—Quadropod.

Field procedure. To use this microsite technique effectively, establish a systematic series of quadrat plots over a larger area. For trail monitoring, determine plot locations along the trail at specified intervals after a randomly selected starting point. Use two stakes driven flush with the ground to locate two corners of the quadrat frame. For localized areas such as campsites, establish a series of transects across the area by tagging surrounding trees and running string between them. (String used for establishing transect lines should be stable enough not to stretch and sag when pulled taut.) Establish sample plots at intervals along each

transect. Another method for campsites is to work from an established center point. Determine azimuths at right angles to each other (e.g. 45, 135, and 315°) and establish quadrat plots at specified distances from the center point along each azimuth (Figure 3).

When the quadropod with attached quadrat is in place, remove all overhanging leaves and branches that obstruct the view of plants inside the quadrat. Set the camera for the appropriate exposure and focusing distance. With the electronic flash and sun screen, the camera shutter and aperture settings should not change.

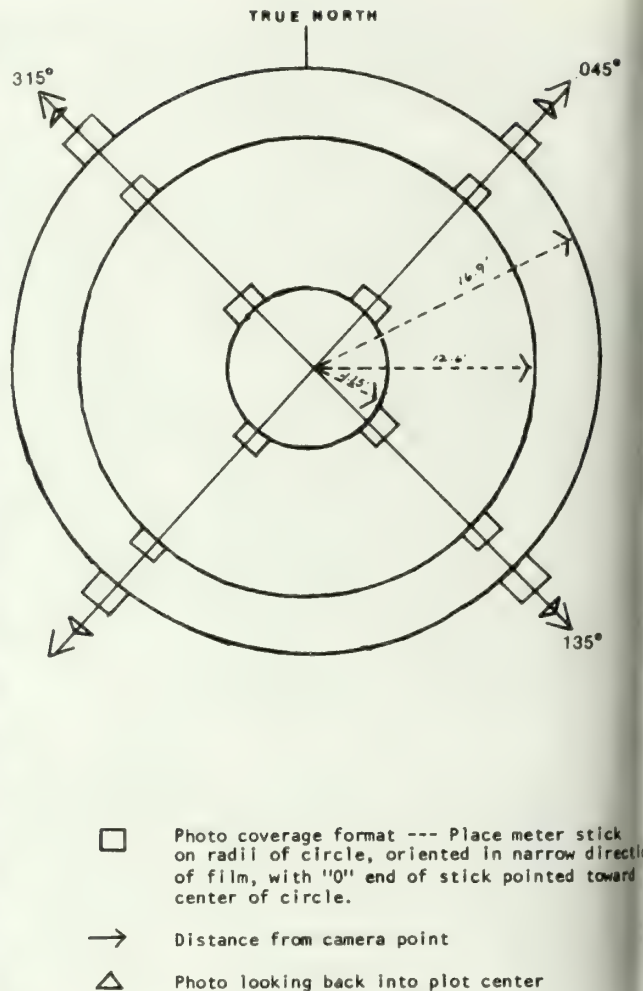


Figure 3.—Sketch of quadrat plots located along radii from a center point.

Take documentary photographs of the entire study area to aid in relocating it. In addition, an oblique (sidelong) photo of each quadrat may be useful. While no measurements can be made from these, they may aid in determining species composition.

Lab procedure. Enlarge prints or slides (using a Kodak Ektagraphics or similar device) to a convenient size. Cover the print or viewing surface (such as that provided by the Ektagraphics) with acetate or other transparent material. Outline objects on the acetate with a grease pencil (Figure 4). Trace the delineations from the acetate to graph paper for areal measurements (Figure 5).

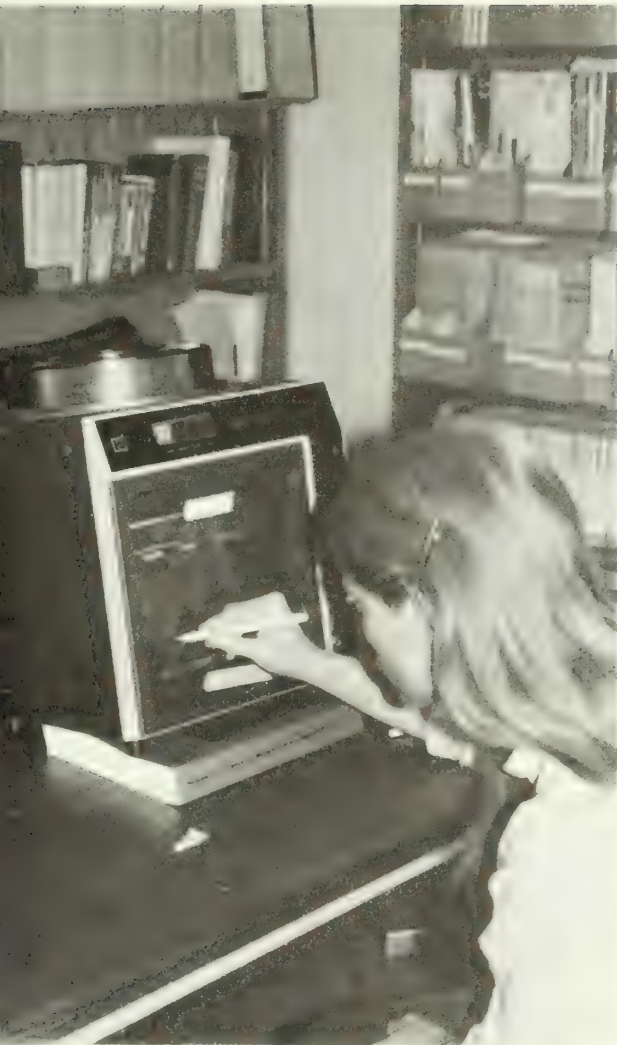


Figure 4.—Tracing the ground cover delineations onto acetate from the enlarged photograph.



Figure 5.—Tracing the ground cover delineations onto graph paper.

Depending on the objectives of the study, a number of analyses can be performed. Individual plants or groups of plants of the same genus or species can be counted and measured. Areas of disturbed ground cover, including litter, can be outlined and rated by degree of disturbance. Areas of exposed mineral soil can be marked and measured. Plant survival and changes in conditions of the forest floor can then be determined. Comparisons may be made between whole quadrats or between subdivisions within each quadrat.

Discussion. The principal advantage of quadrat photography is the shift in time and expense from the field to the lab. Professional research analysts need not perform their task in the field, where such things as weather conditions might affect the reliability of the analyses. Photographs also provide records of raw data that can be used for different analyses later.

Vegetation height is a critical limiting factor for this type of photographic monitoring. High vegetation affects fo-

cusing, flash exposure, and visibility of the area beneath it.

For resource managers seeking a quick assessment of site conditions, the cost of establishing a series of plots for each site and analyzing the data as described here may be prohibitive.

Quadrat photography has been used primarily as a research tool in studies of such things as human impact on wildlands (by the Backcountry Project, NEFES), range vegetation (Ratliff

and Westfall 1973; Pierce and Eddleman 1979; Wells 1971), and vegetation succession (Tueller et al. 1972; McKendrick 1976). The Ratliff and Westfall monitoring technique is worth elaborating on because it is rapid and uses lightweight equipment. Their camera support is a bipod fabricated from 1/2-inch electrical conduit with 1-foot-square quadrat frames (Figure 6). The quadrat frames are fitted with upright posts; the bipod can be slipped over them. With extra frames, one quadrat is set up while another is being photographed. The system uses the Honeywell Pentax stereoadapter, a device that splits the image and provides stereo viewing of the quadrat on a single commercially printed photo (Figure 7).

While backcountry recreation managers may not be as concerned about empirical data as researchers are, they could certainly use quadrat photography for illustrative purposes. They may use the technique to document, in detail, trail widening problems, campsite deterioration due to human impact, or improvements due to rehabilitation programs.

Trail Mosaics

This is another form of vertical ground photography (i.e., with the camera pointing straight down) devised at the NEFES Backcountry Project to monitor vegetation changes and trail widening. A series of photographs are taken across a trail transect and pieced together to form a strip representation of the area beneath the transect.

Equipment. Trail mosaics require a camera and flash system with a tripod. The tripod's center post must be reversible so that the camera can be mounted between the legs of the tripod, or the head must tilt forward. Because the subject is close to the camera, a single-focal-length macro lens would be useful, but it is not essential. One, or preferably two, electronic flashes and a cloth sun screen are necessary for uniform lighting. At such close range a ringlight would simplify the setup and provide the most even, shadowless light.



Figure 6.—Bipod with 1-square-foot quadrat frame.

Color negative or slide film is appropriate for this technique. Commercially developed color prints from negatives are a convenient size for this type of display. Slides are more practical if, in addition to a mosaic, some quantitative grid analysis is desired.

Several items are required to establish the transect and photograph it properly. Two fiberglass metric tape measures, string, two nails, tree tags, a plumb bob, and a hammer are necessary to set up the transect. A compass and clinometer are useful, and a small spirit level is necessary to adjust the camera position properly.

Field procedure. The procedure for establishing and measuring trail transects is described in detail by Leonard and Whitney (1977), so only a brief treatment is presented here. A transect is established by stretching a fiberglass tape measure and a string between two trees that permit a roughly perpendicular crossing of the trail. The tape measure is required to determine intervals for trail profile measurements and camera positions across the transect. The string can be drawn tighter than the



Figure 7.—Camera fitted with a stereoadapter.

tape measure, so it is used as the actual baseline for vertical profile measurements and camera height.

If a trail profile is desired, use a second tape measure with plumb bob attached to take vertical measurements at 10-cm intervals across the transect. Record the distance from the trail surface to the string at each measuring point. Position the camera at intervals along the transect that permit an overlap of about 25 percent between film frames. Record each camera position along the horizontal tape. To facilitate accurate camera alignment at a particular horizontal tape reading, mark the center of the camera bottom. To assure that the resulting photographs will piece together properly, the edge of the film in the camera must be parallel to the string at each repositioning.

Make all exposures with electronic flash to assure uniform lighting. At the close range prescribed, one flash may be difficult to position to avoid shadows and provide even lighting across the whole frame. A ringlight or two flashes rigged at about 60° angles ensure the best lighting for this technique.

Lab procedure. Trim and piece the together edge to edge to form a mosaic of the trail transect. If the transect was measured, mount the profile on the same display board with the mosaic to provide a graphic and qualitative representation. Analyze the transect profile to determine soil loss and changes in trail width. Use the photographs to illustrate changes in the mineral/soil/litter ratio, plant survival, and relative occurrences (Figure 8).

Discussion. Information regarding vegetation types, amount of litter and soil, etc., is a necessary adjunct to profiles. The best record is perhaps provided by trail mosaic photographs, which can be verified and analyzed in varying degrees of detail in the comfort and convenience of the office or laboratory.

However, too much relief in the ground surface or vegetation height can create difficulties. Beside the problems of focusing, uneven flash illumination, hidden vegetation, piecing the photographs together is more difficult where the relief is too great.

The time required to set up the camera for an entire mosaic may also be prohibitive. This could be reduced somewhat by photographing only the right and left trail edges where the most changes normally occur, but some information and a degree of effectiveness of the strip mosaic representation is lost in doing so.

Trail mosaics can be effective supplements to other systematic trail sampling procedures for documentary or scientific purposes. Information obtained from trail transect monitoring can be used by researchers to determine relationships between site conditions, trail condition and trail degradation. Managers are able to use such information to improve the design and location of new trails and the reconstruction of old trails (Bard and Whitney 1977).

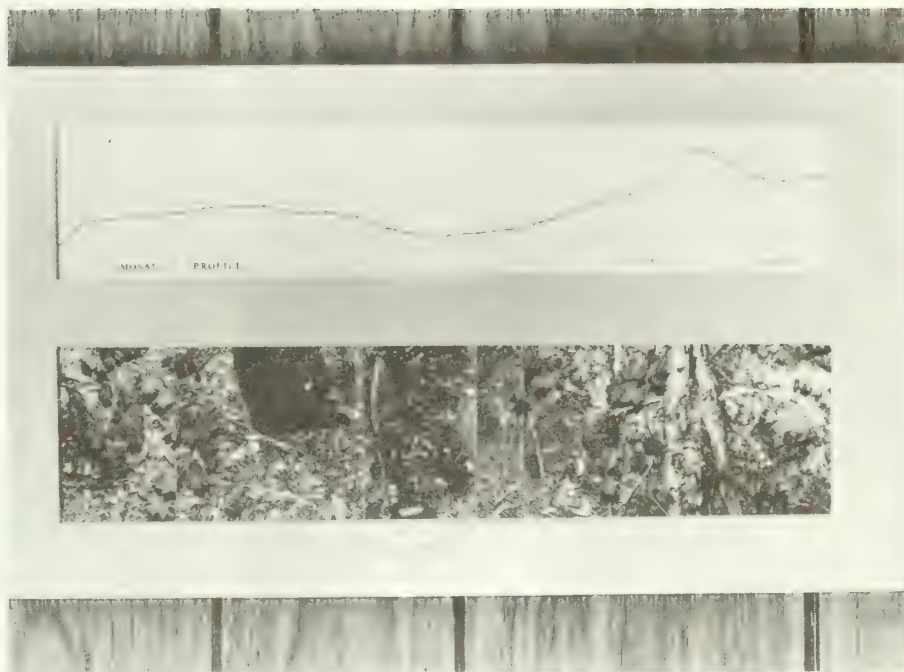


Figure 8.—Trail profile and accompanying mosaic.

Stereo Trail Transects

Drawing on methods introduced by Walker (1968), Rinehart et al. (1978) devised a technique for analyzing soil loss at selected trail transects to determine rates and patterns of trail entrenchment.

Equipment. This single-camera stereo system is based on the use of the Hardy flip-flop attached to a tripod (Figure 9). This stereoboard can be used with a 35 mm or a 2 1/4 inch camera equipped with a normal lens for minimum distortion. A 2 1/4 inch camera is superior to stereo viewing of contact prints and gives better image quality. An electronic flash may be helpful, but is not essential. Black and white film is recommended, since no advantage is gained from the use of color film.

Items necessary to establish the transect are: two tent stakes, two survey pins (or suitable substitutes for these items), a tape measure or string, and a white target card.

Field procedure. To establish the transect, drive the tent stakes flush with the ground on both sides of the trail so that a line between them is perpendicular to the treadway. Place the stakes about 2 feet beyond the trail edge to minimize accidental or malicious tampering and to allow for future trail widening. The stakes should be secure enough to resist movement so that they will be at a consistent height at each rephotographing. Record the distance between the stakes to aid in verifying photo scale calibrations and finding the second stake after the first has been found.



Figure 9.—Hardy flip-flop with a 2 $\frac{1}{4}$ -inch camera.

Place the two surveying pins plumb (vertically) over the stakes to serve as references for the stereo plotting procedure. Stretch the tape measure between the two tent stakes, holding it exactly on top of them. Write the transect number on the target card and place it on edge directly beneath and parallel to the transect line.

Set up the tripod 15 feet downhill in the transect. Mount the camera on the stereomount. Position the camera so that the center of the lens is approximately level with the center of the enrichment area (Figure 10). Make sure the film plane is parallel to the transect by using a compass to coordinate the alignment of the transect and stereomount. Level the stereomount. Focus on the target card markings, and expose a series of photos starting from the left side.

Some deviations from the foregoing camera positioning are permissible under certain circumstances. A standard camera-to-transect distance is advisable in order to keep the photo scale consistent for all transects; however, a greater distance may be required for complete coverage of some wide trails. In addition, a shorter distance may be necessary on steeper trails to keep the camera level. The camera may be tilted if absolutely necessary, but the angle must be recorded, from a clinometer, and accurately duplicated on subsequent photo missions. For hand-drawn cross-sections using simple stereo cameras, accurate positioning of the camera is very important. Minor aberrations are acceptable if more sophisticated stereo plotting devices are available.

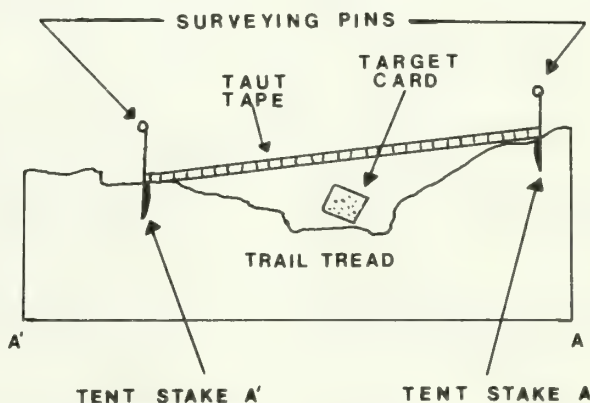
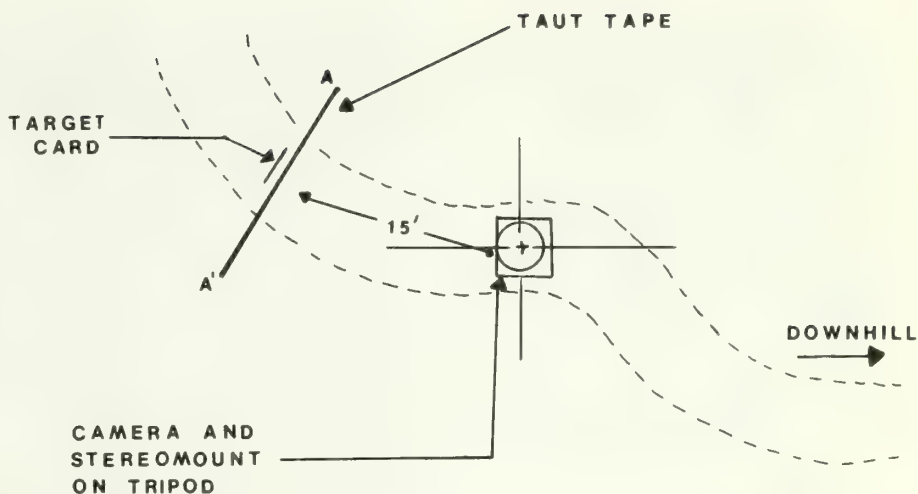


Figure 10.—A typical set-up for photographing a trail transect.

Lab procedure. Contact prints from 2 1/4 inch negatives are suitable for analysis, and either 2 1/4 inch or 35 mm negatives can be enlarged if the entire negative is printed, without cropping.

Determine the scale of the photo. First measure the size of the target card image with a pocket comparator to the nearest .01 cm. Calculate the representative fraction (RF) using the following formula:

$$RF = \frac{\text{target card width in photograph}}{\text{actual target card width}}$$

Make ground measurements by multiplying any photo measurements by the inverse of the RF.

Determine the area of the trail cross section. Cover the photo with acetate or similar transparent material. While viewing through a stereoscope, draw a line along the ground directly under the reference line from one survey pin to the other. Using a polar planimeter, measure the area between the reference line and ground line. Multiply this measurement by the square of the inverse RF to determine the actual cross sectional area. Subtract from previous measurements for that transect to determine the amount of net soil loss.

Discussion. This technique is a photographic alternative to on-site measurement. Rinehart et al. (1978) attributed several advantages to stereo trail transects including: (1) photos can reveal actual trail configuration better than points plotted on a graph from numerical measurements; (2) photo analysis can be performed any time to check for inconsistencies or questionable measurements (field measurements cannot be repeated); (3) photos can be more efficient in short season areas (the more time-consuming measurements are performed in the lab or office rather than in the field).

Disadvantages of stereophotographic transects are associated with the lab analysis. Vegetation in front of the transect may prevent the photo interpreter from plotting an accurate ground line. Although skilled photogrammetrists are needed to achieve the most accurate results from stereo photographs, less skilled personnel can obtain on-site measurements. Rinehart et al. (1978) found that ground measurements were also more consistent between observers than photo measurements, although the levels of error were acceptable in both tests.

The total cost of photographic transect monitoring is greater than that of on-site measurements. More expensive equipment is required, and more time is consumed in the lab analysis. An alternative to stereo monitoring which has been used at the NEFES Backcountry Project appears to reduce the cost differential somewhat: Instead of determining the ground line beneath the transect from stereo photos, the line is established on-site by using a nylon string. The string is stretched between the transect stakes and released slowly on one end. The inherent elasticity of the nylon causes the string to lie along the contours of the trail. Since the string establishes the lower base line, one photograph instead of two can be taken. Advantages of this method are: (1) there is no restriction on the size of the enlargement of the photo for analysis, and (2) there is no error due to faulty stereo viewing.

The typical objective of photographic trail transect monitoring has been to provide quantitative research data for statistical analysis to determine correlations between site conditions and use factors. Such information could be useful in management planning. Managers could also use the stereo or monoscopic photographs to display soil-loss problems for educational purposes.

Campsite Panoramas

Walker (1968) and Lucas (1975) have used site panoramas to provide overviews of large recreation sites. Photographs are taken with ordinary photo equipment and pieced together form a panorama for qualitative assessments of change in the area.

Equipment. A camera (either a 2 or 35 mm) and a tripod are the basic necessities. Carry both a normal and wide angle lens if they are available. Use the normal lens where camera placement is not restricted. Where space is limited, a wide angle lens with a field of view around 65° (35-mm lens for a 35-mm camera, or a 65-mm lens for a 2 1/4-inch camera) should provide ample coverage in most situations. Wider angle lenses are subject to less tolerable degrees of distortion, which makes piecing the photos together more difficult. A perspective-control lens would provide maximum coverage with minimal distortion, but it is not essential. A focusing screen with a grid is useful. Fast color negative film is best because of its excellent ground-coverage differentiation, wide exposure latitude and long contrast range.

The camera is leveled with a spirit level and its azimuth measured with a compass. A clinometer can be used for measuring the degree of forward tilt when necessary. A smooth plate mounted between the camera and tripod provides a convenient surface on which to place the level and compass. A plumb bob hung from the tripod center post aids in locating the camera directly over the photopoint (Figure 11).

Field procedure. Choose a photopoint that permits the most thorough representation of the area with consideration for future changes. If there is structure (e.g., a hiker's lean-to) on site, a view of the area to the front of

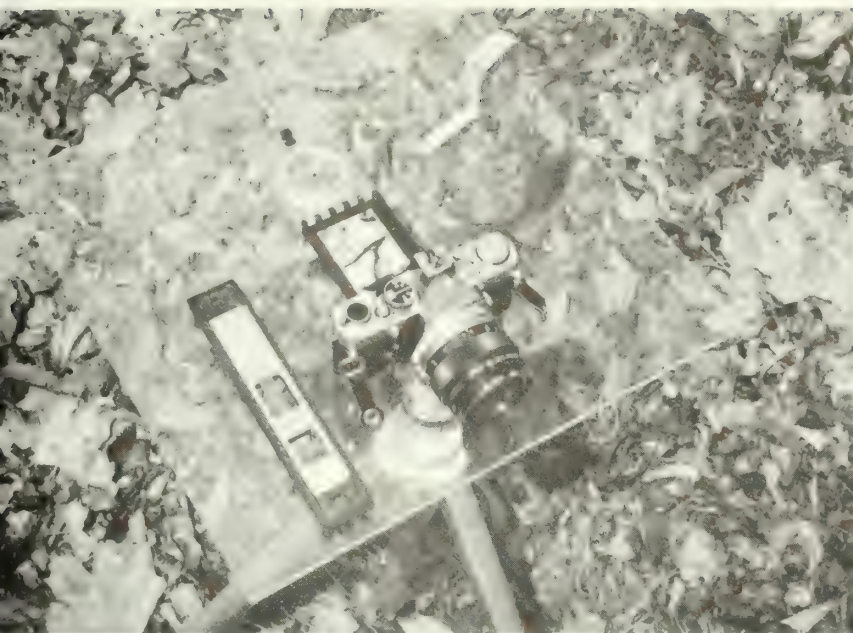


Figure 11.—Camera set-up for site panorama.

s of the structure is most useful; dictates a 140 to 180° panorama, n from the center front of the struc- For sites without structures, 360° ramas can be made from a central opoint. The ground cover, shrub ening, and tree trunk conditions are should be recorded.

Camera height needs to be con- , and the camera ideally should be throughout the rotation. If a level era position cannot be maintained very frame (and a Perspective rol lens is not available), the cam- may have to be tilted forward. If this ne, the angle of tilt must be con- throughout the rotation. Record usual photopoint information (cam- lens and film used, witness tree in- ation, and sketch map), camera nt, and degree of forward tilt (if

When the camera is positioned, take a series of photos from left to right. If the panorama covers 360°, use a target card positioned at true north about 10 to 20 feet from the photopoint or mark the beginning photo. Each photograph should overlap the preceding one by 25 to 30 percent to reduce the effect of lens distortion, which is most prominent at the frame edges. Record the azimuth of each camera sighting. To reduce differences in magnification between successive photos (which prevent good matchups when the photos are pieced together), Blaker (1976) suggests that you first measure and mark the desired overlap on both sides of the camera's ground glass (or use grid lines if available) so that the joining point of the photos will always be equidistant from the lens axis, and second, that you do not change the focus during the panorama series.

Lab procedure. The photographs are trimmed and pieced together from left to right. It is important to trim both adjoining photographs in the middle of the overlap area. This removes the portions of the images where the distortion is most evident. With a straightedge and razor blade, trim the left photo first, align it over the right photo and trim that one. Mount the photos on mounting board. On the back of the board, mount copies of the site data, photopoint reference maps, and any documentary photos taken at the site. Keep a file of the duplicates of all mounted photos and maps for use in the field during subsequent photo sessions.

Compare successively taken panoramas for changes in tree and shrub conditions and numbers, evidence of use (i.e. litter, shelter alterations, tree damage), and the amount of bare, compacted soil in the area.

Discussion. Photo distortion and match-up procedures make areal or other measurements from panoramas impractical. Any quantitative data from panoramas could only be in the form of numerical counts of such things as trees, fire rings, etc.

Weather conditions are a limiting factor in achieving usable results. A bright but hazy day provides the best lighting for this type of photography. Bright sunlight causes shadows and differences in exposure between frames, and you may have to shoot directly into the sun.

This technique for monitoring provides a broad overview of larger backcountry sites. Panoramas can provide direction for management, training tools for personnel, or visitor education material. They may also be used by researchers in combination with other data about the physical characteristics of the site and use levels to give a better understanding of their interrelationships, which can be beneficial for management planning.

Perspective Grid Photography

This technique was devised at the NEFES Backcountry Project. It uses a perspective grid to obtain quantitative information about ground cover changes from single photographs.

Equipment. Either camera format may be used, but a wide angle lens with an angle of view around 75° is important. A tripod, plumb bob and metered steel or woven metallic tape measure are also necessary. If a 35 mm camera with interchangeable focusing screens is available, a screen with center cross hairs would be useful to center the plot center in the frame and to adjust the side tilt of the camera.

Since some control must be exercised in the photo enlarging process, either in-house darkroom facilities or custom photo printing are important. The type of film to use depends on the capabilities of the darkroom. Black and white film would be the least restrictive. Grain may be a consideration in determining what speed film to use, since enlargements up to 11 by 14 inches are recommended.

Field procedure. This technique is accomplished in two phases. A perspective grid is first photographed for subsequent use with photos taken in the field. To establish the grid, lay out a 4- by 4- or 6- by 6-meter plot on an asphalt surface such as a parking lot. Draw in grid lines at 1/2-meter intervals with white chalk. Anchor the tape measure at the grid center and extend it along the corresponding grid line toward the camera point. Mark the tape where it intersects each grid line. Establish a suitable camera height (1.5 meters is recommended), and move the camera and tripod along the tape until the grid fills the viewing screen. Locate the camera point on the tape with a plumb bob.

In the field, choose a central point for the study area. Anchor the tape at that point with a visible stake (for the photographic session only—afterward mark the center point with an unobtrusive marker for later relocation). Extend the tape toward a suitable photopoint location and anchor it beyond the camera point marking on the tape. Position the tripod over the camera mark on the tape with a plumb bob. If the ground is undulating, pull the tape taut so that it is horizontal from the center point to the camera point, and measure the camera height from the taut tape instead of the ground level. Record the azimuth of the tape from center to camera position, and establish a photopoint on the ground under the camera.

Adjust the camera so that the plot center is in the center of the frame and the bottom of the frame is at right angles to the tape.

Lab procedure. The perspective grid image produced by the method described here has a width-to-height ratio of 5 to 2. To enlarge the grid to a workable size, print each half of the single negative on 11- by 14-inch photo paper. Piece the two halves together to form the final image. Trace the grid image on an acetate overlay. Add 1/2- or 1/4-meter lines to the overlay to aid in ground cover delineations.

Enlarge the photograph of the field plot in the same way, producing a pieced-together print. Orient the perspective grid overlay on the plot photograph by matching the center stake and marked points on the tape with the appropriate grid lines.

Delineate borders of vegetation types (such as grass-like, herbaceous or woody) and mineral soil. Transfer the delineations from the perspective grid to a square grid (bird's-eye view) by examining points where the mapped bor-

ders cross the grid lines. Estimate the area of each type of ground cover or bare soil with a dot grid.

Discussion. Topography is the principal problem with this technique. The grid is photographed on a flat surface, whereas the field site is often undulating or sloping, causing altered perspective and greater distortion, and reducing the accuracy of measurements. The technique is better suited to field areas than to forests because tree trunks can obscure much of the ground cover in an oblique photograph. The largest area that can reasonably be represented is 36-square-meter plot.

In the lab, there are several sources of error that are difficult to control. Piecing together the photos is one source. Transferring the delineations from the perspective grid to the square grid is a more serious source of error, especially when a mapped zone does not cross any grid lines.

As with panoramas, lighting can be critical to obtaining usable results. Even lighting is essential for accurate mapping. This may necessitate shooting only on slightly overcast days.

This monitoring technique has a certain limited applicability where less-than-perfect, but greater-than-rough estimates of ground cover changes are required at larger sites.

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Resource change can be monitored using photographic methods. Both microsite and macrosite techniques suitable for backcountry use are described and discussed in detail. The microsite techniques, including quadrat photography, trail mosaics and photographic trail transects, are generally the more expensive, requiring more time or specialized equipment in the field or lab than microsite techniques. The data obtained is detailed and quantifiable to a degree that may be acceptable for research purposes. Macrosite techniques, including panoramas and the monoscopic perspective grid technique, are less likely to provide research data, but are useful for qualitative assessments.

ODC 907.2

Keywords: Microsite; macrosite; quadrat photography; trail mosaics; trail transects; panoramas; perspective grid

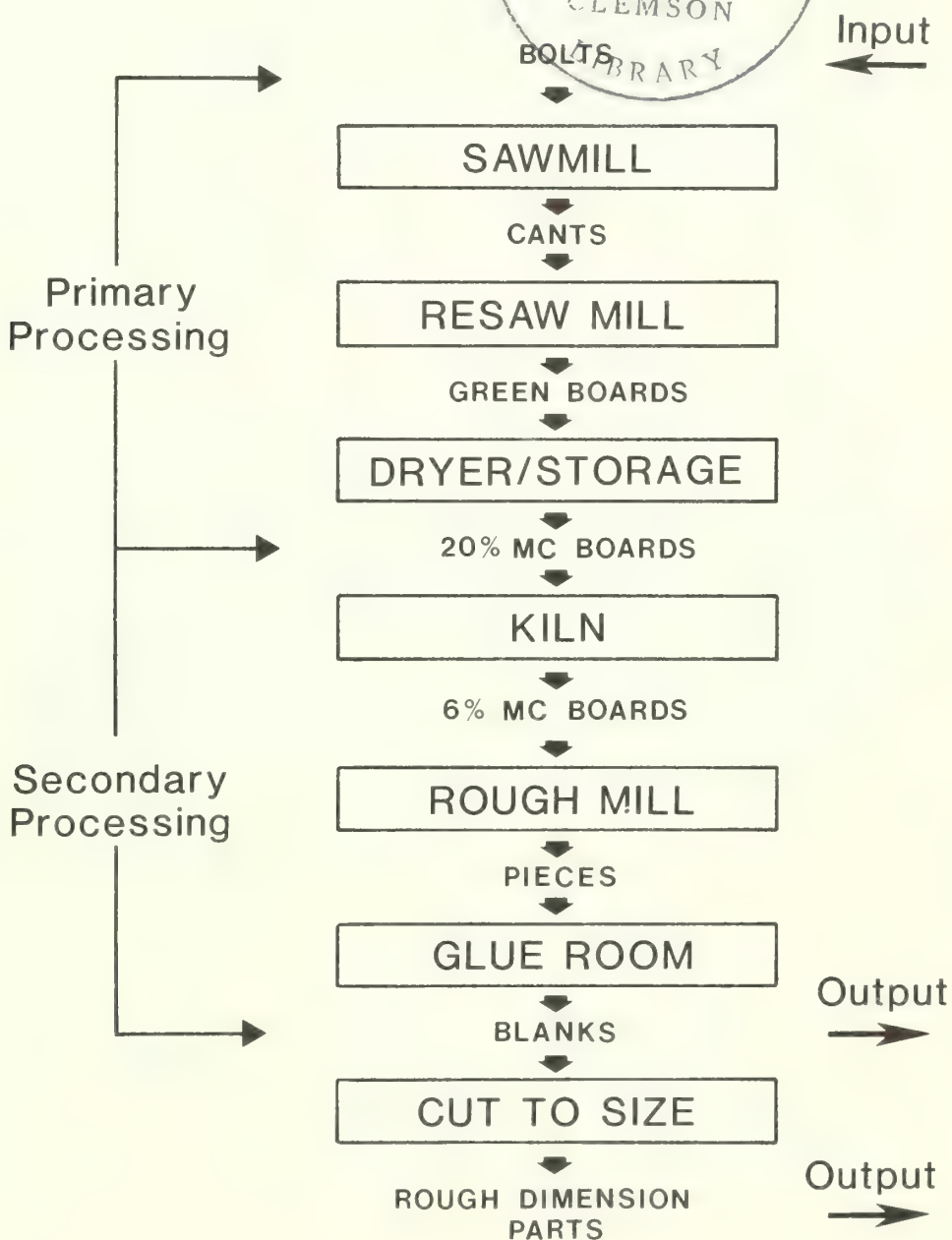
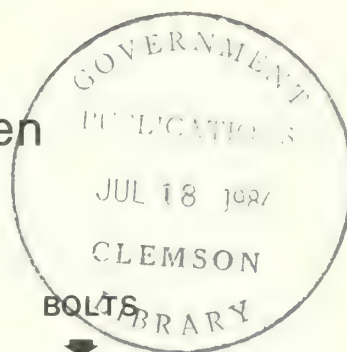
Headquarters of the Northeastern Forest Experiment Station are in Broomall, Pa. Field laboratories are maintained at:

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A Sample Plant Design for System 6

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Abstract

A plant to make standard blanks from cants by System 6 can be assembled from off-the-shelf equipment with few modifications. From the production rates and manpower requirements of each piece of equipment, we designed a typical plant and determined by economic analysis that it could return 21 percent on an investment of \$2 million by making blanks for sale from purchased cants.

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uction

System 6 is a new technique for processing small, low-grade hardwood into high-valued blanks (the flow is shown in Figures 1 and 2). This timber is available in quantities from small-diameter (1 to 4 in. dia) Grade 3 or local-use logs and small timber not normally harvested. Blanks are edge-glued panels constructed to standard qualities, species, lengths, and widths. Blanks are used by furniture and cabinet manufacturers of No. 1 Common and Better grade lumber. Lumber must be edge-glued and sent through a rough mill before it is ready for ripping to final sizes.

This paper is one of a series describing System 6 concepts. The differences between System 6 and conventional hardwood processing have been explained by Reynolds and Gatchell (1979). The System 6 technology was explained in a second paper by Reynolds and Gatchell (1982). Blank sizes and their uses have been explained in a third paper by Araman et al. (1982).

In this paper, production rates and power requirements are calculated separately for each major processing equipment. The total rates are then used to develop typical System 6 processing requirements from a preliminary study (Reynolds and Araman 1982). The economic feasibilities of the system are then tested by cash flow analysis (CFA). A complete discussion of the system together with other System 6 examples, is given in a companion paper.¹

Reynolds, Bruce G.; Reynolds, Hugh W. (1982). Alternatives and economic analysis of System 6 processing. (In preparation for publication, Forest Sciences Experiment Station, U.S.D.A. Forest Research Center, Princeton, WV.)

Plant Specifications

Companies that make living room furniture need both frame parts and clear parts. We will consider building a new plant near a supply of low-grade, small-diameter white oak timber. This plant will make blanks and ship them to furniture plants. Annual production will be 1.55 million square feet of frame blanks and 0.45 million square feet of clear blanks, for a total of 2.0 million square feet. The blanks will be sold to the furniture plants at market prices of \$1 per square foot for frame blanks and \$1.70 per square foot for clear blanks.

Capital investment will be limited to \$2 million. A 20-percent after-tax return on investment (ROI) will be required over the proposed plant's 10-year life.

Plant Design

A single-shift plant to operate 240 days per year will be designed. CFA will then be used to determine whether this design meets the \$2 million maximum investment and the 20-percent minimum ROI requirements. If the requirements are met, the plant design will be acceptable. If not, alternative designs will have to be evaluated. Also, additional designs can be tested to determine whether there are better designs that require less capital investment and give a higher profit (ROI).

The annual input board requirements are as follows:

Blanks	Output		Yield		Input	
	(ft ²)				bd ft	(%)
Frame	1,550,000	÷	0.56	=	2,770,000	73
Clear	450,000	÷	0.45	=	1,000,000	27
Total	2,000,000				3,770,000	100

A research study (Reynolds and Araman 1983) showed that poor-quality white oak boards gave a 56-percent yield of frame blanks. The better quality boards yielded 45 percent in clear blanks. In that study, 68 percent of the board footage was in poor boards. As 73 percent of the boards used here will be made into frame blanks, the white oak board quality is well suited for this use.

With single-shift production 240 days per year, the daily input will be 15.7 Mbf (thousand board feet). The production rates for the principal machines and operations are shown in Table 1.

Raw material will be in the form of cants 6 and 8 feet long. One forklift will unload trucks and put cants into storage or into the resaw mill. The cant receiving and storage area, as well as the rest of the plant layout, is shown in Figure 3.

The resaw will make cants into boards. With the shift input rate at 15.7 Mbf, only one resaw is needed. But two stackers will be required, as one stacker can only handle 10.9 Mbf per shift. A crew of nine is required: one for cant input to work with the cant storage workers; one to feed the cants and operate the cutoff saw; two to operate the cant gang rip saw; two per stacker (two stackers); and one to band the stickered board stacks.

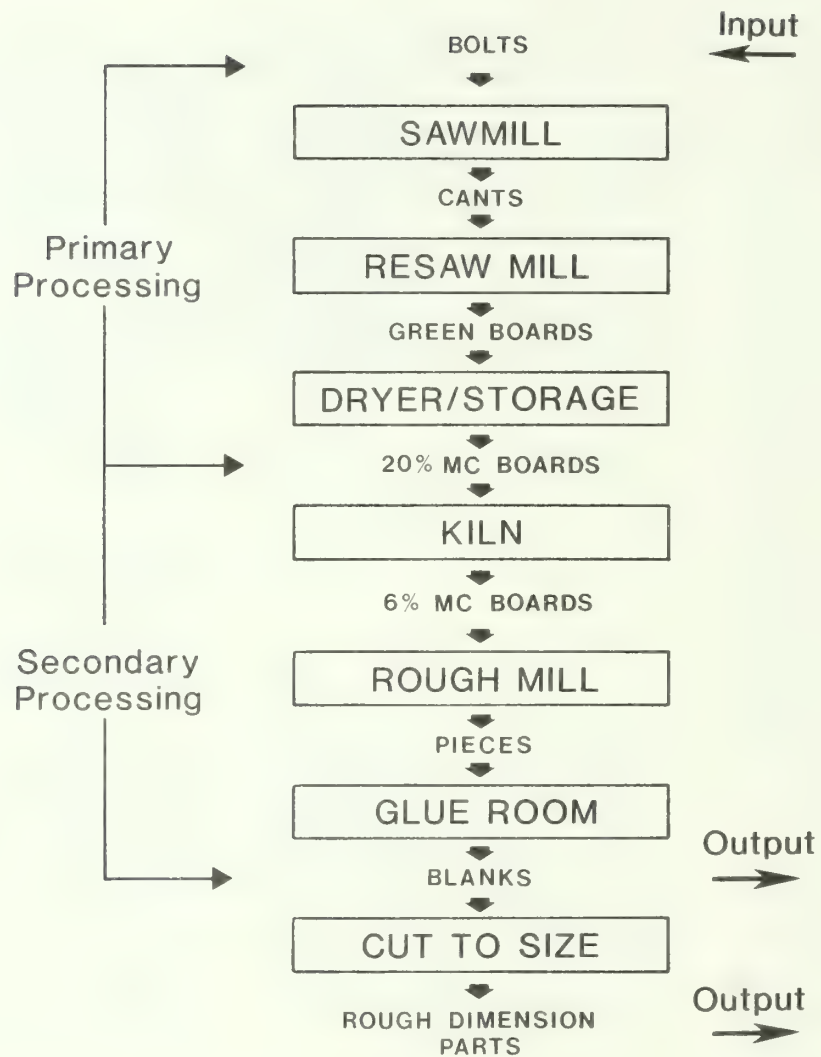


Figure 1. S/6 PROCESS FLOWCHART

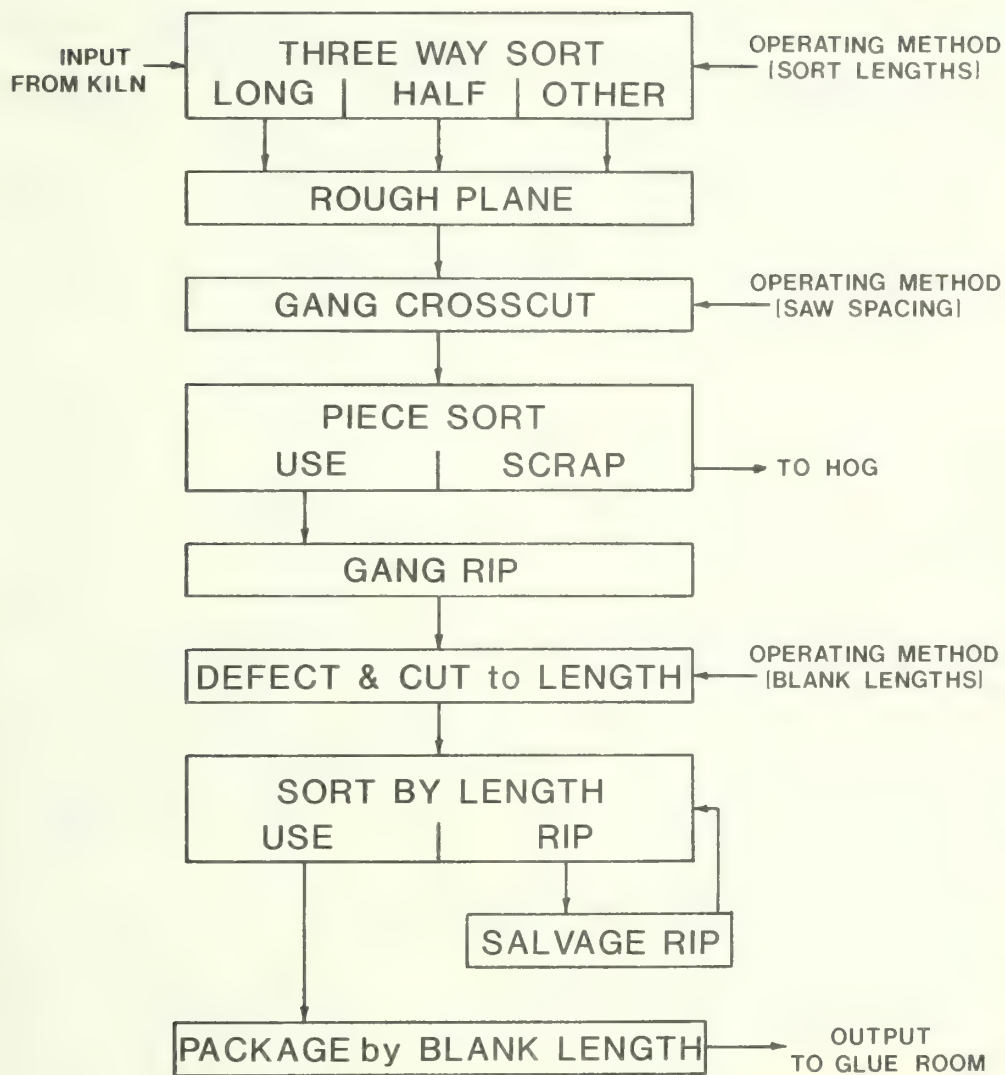


Figure 2. S/6 ROUGH MILL FLOWCHART

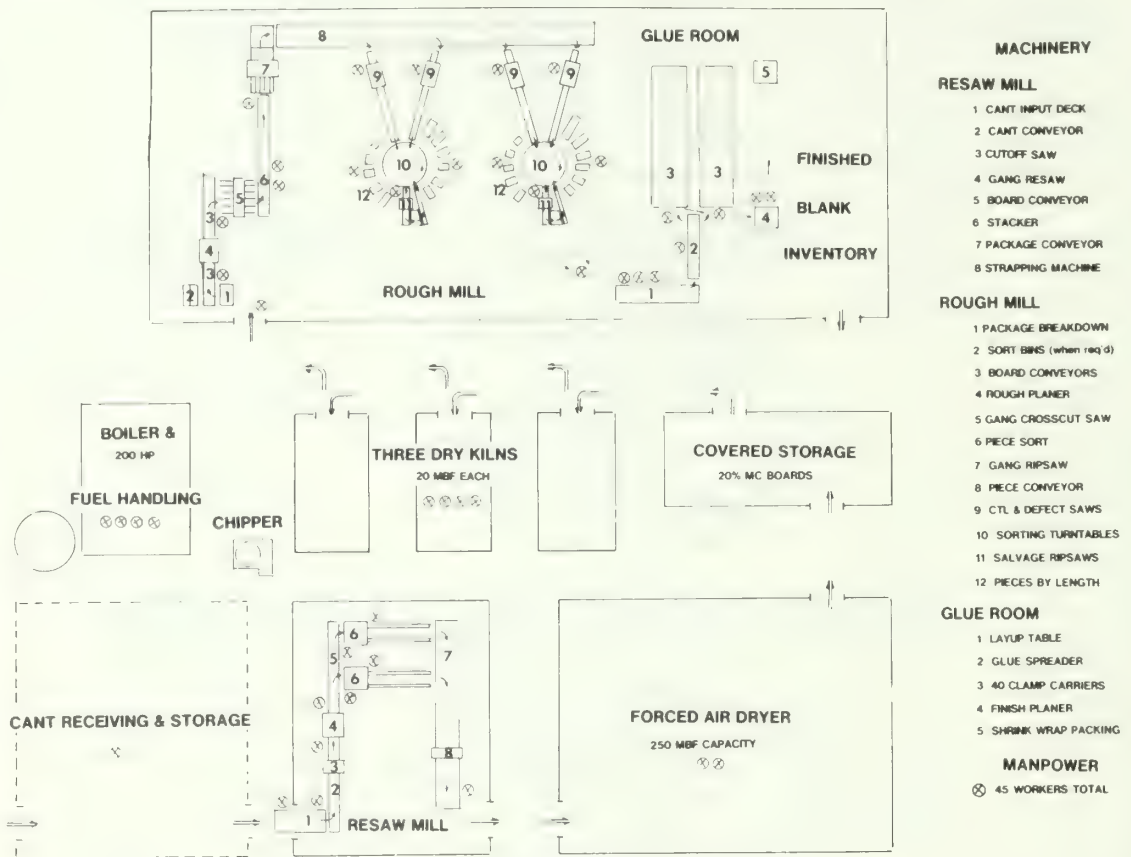


Figure 3. - TYPICAL S/6 PLANT - 16 MBF/SHIFT INPUT CAPACITY NO SCALE

Table 1. Machinery production rates

Processing step	Production rate ^a bd ft input/shift
Cant gang resaw	28.6 Mbf/shift
Board stacker	10.9 Mbf/shift
Dryer	50 Mbf each
Dry kilns	20 Mbf each
Rough mill	
3-way sort	13.9 Mbf/shift/operator
Rough plane	30.0 Mbf/shift
Gang crosscut	21.0 Mbf/shift
Piece sort	7.6 Mbf/shift/operator
Gang rip	62.5 Mbf/shift
Defect/cut-to-length	4.2 Mbf/shift/operator
Sort by length	5.7 Mbf/shift/operator
Salvage rip	16.0 Mbf/shift

^aProduction rate formulas and their derivation are available from the authors.

Low-temperature dryers are used to reduce the moisture content (MC) of the green boards to 20 percent. With a 21-day average drying time, 15 Mbf of dryer capacity will be needed. Since the dryers are built in 10 Mbf units, 5 units or 250 Mbf total capacity will be bought. Two workers in one shift will load, unload, and run the dryer. The dryer will work continuously and unattended at other times.

The stacks of boards at 20 percent MC are held in the covered storage until required for blank production, when they are brought to the kilns for drying. On the average, 120 hours of kiln time, or 5 days, will be needed to dry them to 6 percent MC. Therefore, kiln capacity of 52 Mbf is needed. Since the kilns are built in 20 Mbf units, three units or 60 Mbf total capacity will be bought. The kilns will be operated by four workers who will each work a 42-hour week.

The rough mill operation (Fig. 2) starts when the kiln-dried stacks of boards are brought to the rough mill from the kilns. One forklift is given this task.

One operator feeds the two-sided rough planer and does the three-way sorting. This requires 3 seconds per board, which translates to 13.9 Mbf per shift. But not all operating methods require sorting, so one worker can handle the job. The two-sided planer can process 30.0 Mbf per shift, so only one is used. The three-way sorting, planing, and gang cross-cutting are coordinated, so all "other" boards are planed and crosscut, then the "half" boards, and finally the "long" boards.

With the feed chain at 40 feet per minute, each gang crosscut saw can process 21.0 Mbf per shift. Only one operator is needed to feed this machine. Two seconds per piece, on the average, will be allowed for each operator behind the gang crosscut saw to inspect the pieces. Pieces with a 1½-by 15-inch defect-free area will be accepted and all others will be scrapped. Each operator can process 7.6 Mbf per shift, so two piece sort operators are used.

The gang rip saw has five pockets and feeds at 100 feet per minute. Such a machine, fully loaded at all times, could handle a rough mill input rate of 62.5 Mbf per shift, so obviously only one is used. One operator is required to put the pieces into the proper input bin pocket. The ripped pieces automatically fall onto a cross conveyor to be picked up by the defecting and cut-to-length crosscut operators.

At the defecting crosscut saws, the operators inspect each piece and, if necessary, crosscut out the end defects. Pieces are made to the longest possible blank length. We have found that an average of 4.5 seconds will be required for each piece leaving the gang rip saw. Each operator can handle 4.2 Mbf per shift, so four defecting crosscut saw stations are used for the 15.7 Mbf per shift.

Pieces will be sorted by length manually at an average of 2 seconds per piece. Thus each worker can sort all the pieces generated at an input rate of 5.7 Mbf per shift and three workers can handle the 15.7 Mbf per shift input rate. Salvage rip sawing of 25 percent of the pieces leaving the defecting crosscut saws will require one rip saw.

But we have designed the plant layout so that two defecting crosscut saws will drop their pieces onto one revolving sorting table. Each table will have half the pieces, so sorting on each table has to be done at a rough mill input rate of 7.85 Mbf. Therefore, there will be two workers per sorting table, and one salvage rip saw at each table with a single operator.

In the glue room three workers lay up the pieces to blank width. With a closed clamp time of 60 minutes, 120 sections of clamp carrier will be needed. Two 60-section clamp carriers will be used with one worker per carrier plus a glue spreader operator. Two additional workers plane the dried blanks, package them, and load them for shipment.

A 500K memory minicomputer, with linear programming and inventory software, is used to determine the best way to operate the System 6 mill. The design requirements for this mill are taken from a specific study (Reynolds and Araman 1983); but when other blank requirements are considered, different gang cross-cutting and blank length options will have to be considered (Reynolds 1984). The minicomputer is used to determine the least costly processing methods to obtain the blanks required. The minicomputer will be operated by the System 6 mill manager.

A steam boiler using waste wood (from the System 6 process) for fuel is required to heat the dryers, kilns, and buildings. The boiler specifications, fuel-handling equipment, and costs are taken from manufacturers' recommendations. A crew of four is used for full-time attendance.

**Table 2. Equipment costs—installed
(Prices current: October 1982)**

Item	Cost
<i>Primary processing machinery</i>	
Cant gang resaw: Hazelthorne K140, 11 saws, 10 boards (100 hp)	\$ 22,000
Cant cutoff saw: Hazelthorne R180, 6 × 25 (15 hp)	9,000
Receiving deck, unscrambler and conveyors (25 hp total)	36,000
Two manual board stackers \$7,500 each (10 hp total)	15,000
Board conveyors and strapping machine (25 hp total)	30,000
Hog/screen chip-pac and infloor sawdust/refuse conveyor (75 hp total)	48,500
Forklift 4,000 pounds propane	12,500
	\$ 173,000
<i>Secondary processing machinery</i>	
Package breakdown hoist and 3-way sort conveyors (25 hp total)	\$ 24,000
Rough planer: 2-side 4 × 12 spiral knives (50 hp total)	30,000
Gang crosscut saw: 5-saw variable spacing Stetson-Ross (30 hp total)	54,000
Gang rip saw Stetson-Ross MR-24 modified (100 hp)	60,000
Piece conveyors and piece sort station (25 hp total)	24,000
Four defecting saws \$8,500 each (20 hp total)	34,000
Two rotary sorting tables \$4,500 each (10 hp total)	9,000
Two salvage rip saws w/return conveyors \$8,500 each (50 hp total)	17,000
Forklift 4,000 pounds propane	12,500
Glue spreader, conveyors, and panel layup tables (15 hp total)	15,000
Clamp carrier: Air motors 80 section @ \$65,000; 40 section @ \$35,000	100,000
Panel trimsaw: 3 saws variable spaced (30 hp total)	35,000
Blank planer: 2-side, 2 × 30 spiral knives (75 hp total)	40,000
Dust collection system and bins (50 hp total)	65,500
Minicomputer w/500K memory and software	10,000
	\$ 530,000
<i>Dryers, Kilns, and Boilers</i>	
Boiler 200 hp and fuel handling/storage	\$ 300,000
250 Mbf dryer @ 60¢/board foot capacity	150,000
Three 20 Mbf kilns @ \$2.70/board foot capacity	162,000
Two forklifts 4,000 pounds propane \$12,500 each	25,000
	\$ 637,000
Land, improved 8 acres \$12,500/acre	\$ 100,000
<i>Buildings</i>	
Primary plant 40' × 70' = 2,800 square feet @ \$24/square foot	\$ 67,000
Secondary plant 40' × 150' = 6,000 square feet @ \$24/square foot	144,000
Boiler 40' × 40' = 1,600 square feet @ \$12.50/square foot	20,000
Air dry lumber storage 40' × 60' = 2,400 square feet @ \$12/square foot	29,000
	\$ 260,000
<i>Total Investment</i>	
Machinery: Primary plant	\$ 173,000
Secondary plant	530,000
Total	\$ 703,000
Dryers, Kilns, and Boilers	\$ 637,000
Buildings	260,000
Total	\$ 897,000
Land	\$ 100,000
Grand Total	\$1,700,000

The estimated installed cost for the plant layout shown in Figure 3 is given in Table 2. Costs are those of October 1982.

Economic Analysis

After a proposed plant is designed, the engineering data must be translated into economic terms. A cash flow analysis is made with the economic data. If the CFA shows that the plant specifications are met or exceeded, the proposed plant design will be accepted. If the design does not meet the specifications, a new design must be made and tested.

A number of assumptions and techniques are used with the CFA program:¹

- A 10-year plant life: In 10 years the assets will be presumed sold for their remaining undepreciated value. The working capital will be returned.
- Investment: The internal rate of return (IRR) is based on the entire investment. The source of this investment, whether borrowed or equity capital, is not considered.
- Taxes: The maximum Federal corporate tax rate of 46 percent will be used without any tax sheltering. Investment tax credits will not be used. State and local taxes are taken as fixed costs.
- Depreciation: The 1981 accelerated depreciation allowances are used with 5-year writeoff for machinery; 15 years for buildings, kilns, and boilers; and no depreciation for land.

The economic data, costs, and revenues are shown in Table 3. Sawmills near the new System 6 blank plant will purchase marginal quality white oak bolts (Reynolds and Araman 1983) for \$39 per cord. This is equivalent to \$85 per Mbf by the 1/4-inch international scale, as there are 2.2 cords per Mbf, bolt scale. The sawmills can saw two cants per bolt profitably at \$50 per Mbf, bolt scale. Hauling costs from sawmill to the blanks plant will average \$15 per Mbf. Bolt and cant scale are the same. The cant cost at the blank mill will be \$85 + \$50 + \$15 = \$150 per Mbf. Because the white oak bolts are of

Table 3. Annual operating costs and revenues

Item		Year 1	Years 2-10
Costs: Variable	Cants \$150/Mbf × 12.3 Mbf/day × 240 days/year	\$ 221,000 ^a	\$ 442,000
	Labor 45 workers @ \$6/hour + 2 @ \$10/hour	435,000 ^b	580,000
	Supplies: 1.5 percent of sales	26,000 ^b	35,000
	Utilities: 2.0 percent of sales	35,000 ^b	46,000
	Selling expenses: 5.0 percent of sales	58,000 ^a	116,000
Costs: Fixed	Management and administrative (2 executives; 1 secretary)	80,000	80,000
	Insurance: 2 1/2 percent of value = \$1,600,000	40,000	40,000
	Maintenance: 10 percent of equipment cost = \$1,340,000	134,000	134,000
	Total	\$1,029,000	\$1,473,000 ^c
Revenue:	Frame blanks: 1,550,000 ft ² × \$1.00	775,000 ^a	1,550,000
	Clear blanks: 450,000 ft ² × \$1.70	383,000 ^a	765,000
	Total: 2,000,000 ft ² × \$1.16	\$1,158,000 ^a	\$2,315,000

^aHalf of years 2-10 production.

^bSeventy-five percent of years 2-10 costs.

^c64 percent of sales.

small diameter, the 1/4-inch International scale underestimates the quantity of boards that can be made. Research for this paper showed a 28-percent overrun from bolt/cant scale to boards. Thus the 15.7 Mbf per shift board requirement becomes a 12.3 Mbf per shift cant requirement ($15.7 \div 1.28 = 12.3$).

Plant construction, manpower, hiring, and training will start at the beginning of year 1. By the end of the year, production will be at the design rate. Because of training and construction delays, only half of a normal year's production will be made in year 1; but 75 percent of the normal year's costs for labor, supplies, and utilities will be incurred in year 1. Only 50 percent of the normal year's cant costs and selling costs will be incurred in year 1, but all the normal year's fixed costs will be incurred.

Working capital is required to purchase and maintain a 36-day supply of cants on hand (\$66,000). The blanks customers will have 30 days to pay

for the blanks so an accounts receivable working capital of \$190,000 will be needed. Only \$128,000 of working capital will be required during the first year because production will be only half of that projected. The other half of the total working capital (\$256,000) will be committed at the beginning of year 2.

The capital investment is shown in Table 2. Machinery totaling \$703,000 will be depreciated in 5 years; kilns and boilers totaling \$637,000 will be depreciated in 15 years, as will buildings totaling \$260,000. The \$100,000 in land and improvements will not carry any depreciation. The capital investment totals \$1,628,000 which is \$1,700,000 of real capital plus the first year's working capital at \$128,000.

The CFA shows an IRR of 21 percent. Thus both the maximum capital investment of \$2,000,000 and the required 20-percent minimum rate of return have been met. The proposed design is acceptable.

Summary

Three independent factors must be considered when a System 6 plant is designed:

- Investment: What is the maximum amount of investment capital available and what is the minimum rate of return this investment must earn?
- Blanks: There are 148 different standard-size blanks by quality, thickness, and length. What are the quantity requirements for each of these blanks?
- Raw material: What quality and quantity of small-diameter, low-grade hardwood is available; what will it cost; and what will be the yield in required blanks?

The System 6 plant designer's problem is to find a design that will satisfy the blank demands using the available raw material while staying within the prescribed investment limits.

The demand for blanks can be estimated from the total furniture and kitchen cabinet industry demand as found by Araman et al. (1982) or for a particular part of the industry. In this

paper the second method was used (Reynolds and Araman 1983).

A study of the raw material is necessary to find the yield of the required blanks. Raw material costs are also needed. In this paper we used the results of a study using white oak thinnings to produce frame blanks (Reynolds and Araman 1983).

A System 6 plant design is then roughed out. Machinery, kilns, buildings, land costs, etc., are estimated. This data is put into economic terms and a CFA is made. If the results of the CFA show that the design meets or exceeds the investment requirements, then this plant design is practical.

This System 6 plant design method is an iterative technique. A design is made and tested. If the design meets or exceeds the economic requirements, it is acceptable. Additional designs can be tested to determine whether a better one exists. If the design is unacceptable, changes will have to be made to reduce costs and investment or to improve earnings. In a companion paper¹ the CFA is fully explained.

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Reynolds, Hugh W. **System 6: Rough Mill Operating Manual.** Res. Pap. NE-542. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1984. 27 p.

Reynolds, Hugh W.; Hansen, Bruce G. **A sample plant design for System 6.** Gen. Tech. Rep. NE-87. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1984. 8 p.

A plant to make standard blanks from cants by System 6 can be assembled from off-the-shelf equipment with few modifications. From the production rates and manpower requirements of each piece of equipment, we designed a typical plant and determined by economic analysis that it could return 21 percent on an investment of \$2 million by making blanks for sale from purchased cants.

ODC 836.1; 847.1/2

Keywords: Low-grade utilization, hardwood dimension

Headquarters of the Northeastern Forest Experiment Station are in Broomall, Pa. Field laboratories are maintained at:

- **Amherst, Massachusetts, in cooperation with the University of Massachusetts.**
 - **Berea, Kentucky, in cooperation with Berea College.**
 - **Burlington, Vermont, in cooperation with the University of Vermont.**
 - **Delaware, Ohio.**
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 - **University Park, Pennsylvania, in cooperation with the Pennsylvania State University.**
 - **Warren, Pennsylvania.**
-

Proceedings:

New and Improved Techniques for Monitoring and Evaluating Spruce Budworm Populations



PREFACE

The Canada/United States Spruce Budworms R&D Program (CANUSA) was created in 1977, when the United States Department of Agriculture and the Canadian Department of the Environment agreed to cooperate in an expanded and accelerated research and development effort. CANUSA was aimed specifically at the spruce budworm in the east and western spruce budworm in the west. The broad objective was to design and evaluate strategies for not only controlling budworms but also managing budworm infested forests, to help forest managers attain their objectives in an economically and environmentally acceptable manner.

Population monitoring and evaluation are basic to all insect pest control operations. These activities are routinely carried out by all agencies and departments concerned with forest protection. Furthermore, it is considered essential that, if "integrated pest management" techniques are ever to be fully and successfully applied to the protection of eastern spruce-fir forests, a more efficient method of monitoring low-level, between-outbreaks, populations of spruce budworm must be implemented. Endemic populations which are entering the outbreak phase must be recognized early, so that forest managers have more time to plan an appropriate course of action and make decisions to lessen the impacts of the impending outbreak.

Most forest insect pest survey techniques were developed more than 20 years ago, but there have been some important improvements in these methods during the last few years (the current outbreak). Techniques, such as monitoring spruce budworm populations with sex pheromone traps, have been developed in the last 5 years and have received considerable attention during the CANUSA program. Others, such as the L₂ survey procedures, are constantly undergoing modification and improvement as user experience suggests a better way.

The objective for this workshop was to present, for the benefit of all eastern forest pest control personnel and forest managers, the new or improved methods available for monitoring and evaluating spruce budworm populations. It also provided a forum for discussing ways of using that information to prepare for future outbreaks or mitigate the impacts of outbreaks as they occur. This was one of a series of workshops and symposia organized as part of the technology transfer effort of the CANUSA Program. We hope the information contained in the following papers will be of interest and use to forest protection people and forest managers everywhere.

DAVID G. GRIMBLE
DANIEL R. KUCERA
Co-chairmen and Workshop Coordinators

PROCEEDINGS
NEW AND IMPROVED TECHNIQUES FOR MONITORING
AND EVALUATING SPRUCE BUDWORM POPULATIONS

Sponsored By
Vermont Department of Forests, Parks and Recreation
USDA Forest Service, State and Private Forestry
CANADA/United States Spruce Budworms R&D Program

September 13-15, 1983
Holiday Inn, Burlington, VT

February 1984

Each contributor submitted camera copy and is responsible for the accuracy and style of his or her paper. The statements of contributors from outside the U.S. Department of Agriculture may not necessarily reflect the policy of the Department.



PROGRAM

WELCOME

Brendon J. Whittaker, Secretary of Agency of
Environmental Conservation, Vermont

INTRODUCTION

Frank E. Webb, Forest Protection Ltd,
Fredericton, N.B.

E. Bradford Walker, Director of Forests,
Vermont

DETECTION OF NEW OR INCIPIENT INFESTATIONS

Why should we monitor spruce budworm population trends?

Robert P. Ford, USDA Forest Service

Standardization of monitoring and evaluation techniques: Why?

Louis Dorais, Quebec Dept. Energy and Resources

Using light trap catch to warn of future damage.

Gary A. Simmons and Norman C. Elliott,
Michigan State University

Canadian experience with light traps.¹

Anthony W. Thomas, Canadian Forestry Service

Application of pheromone traps to effectively monitor spruce
budworm populations.

Lawrence P. Abrahamson, Douglas C. Allen and
Gerald P. Lanier, SUNY College of Environmental Science and
Forestry, Syracuse

Video tape: Competing with the spruce budworm in the Lake States.

Bruce A. Montgomery, J. Lindsey Flexner and
John A. Witter, University of Michigan

Sex pheromone traps and lures for monitoring spruce budworm populations -
the Ontario experience.

Chris Sanders, Canadian Forestry Service, Sault Ste. Marie

Monitoring spruce budworm populations with pheromone baited traps.

Douglas C. Allen, Lawrence P. Abrahamson and
Gerald N. Lanier, SUNY College of Environmental Sciences
and Forestry, Syracuse

Panel Discussion - Experience and Problems, Requirements of a
pheromone trapping system.

- Forest Pest management experiences with spruce budworm pheromone trapping.

Dennis J. Souto, USDA Forest Service

- Spruce budworm pheromone trapping; Vermont experiences and problems.

Ronald S. Kelley, Vermont Department of Forests, Parks
and Recreation

- Quebec Provincial Experience.¹

Michael Auger, Quebec Department of Energy and Resources

- Forest pest management concepts of a good spruce budworm pheromone trap.

Daniel R. Kucera, USDA Forest Service

- Experience and problems with pheromone traps.
Jerry R. Williams, International Paper Company, Augusta, ME
- Canadian pheromone trapping.¹
Luc Jobin, Canadian Forestry, Service, Ste. Foy, Quebec

FORECASTING INFESTATION INTENSITY AND DAMAGE

- Ways to reduce errors and improve egg mass surveys.
Gary A. Simmons, Gary W. Fowler and Norman C. Elliot,
Michigan State University
- Automated egg mass counter. AND Demonstration of automated egg mass
counter operation.
Daniel T. Jennings and Loren F. DeLand, USDA Forest Service
- L₂ surveys (soda wash technique).
Henry Trial, Jr., Maine Bureau of Forestry, Augusta
- Evaluating parasitism on sparse spruce budworm populations.
Patricia M. Hanson, University of Vermont, Burlington

PEST MANAGEMENT STRATEGY

- Silvicultural practices of spruce-fir-stands to minimize impact of
spruce budworm outbreaks.
Kenneth F. Lancaster, USDA Forest Service
- Minimizing impacts of future spruce budworm outbreaks.
Philip J. Malerba, St. Regis Corporation, Maine
- How do outbreaks start?
Yvan Hardy, Universite' Laval, Quebec
- Planning now to reduce, postpone or prevent the next spruce budworm
outbreak.
W. Lloyd Sippell, Canadian Forestry Service,
Sault Ste. Marie

¹ No written paper submitted.

Because the spruce budworm is such an important forest problem in Canada, monitoring its break behavior, forecasting and evaluating its impact, and probing the biological dynamics underlying its relationship with its hosts have been preoccupation of Canadian forest entomology for a century. Indeed the development of the general forest entomological establishment in Canada owes its history in large part to this single insect.

The sequence of this development went like this. Studies of eastern outbreaks early in the present century by a few gifted observers made it clear to them that a recurrence of this extraordinary phenomenon only awaited the natural replacement of vulnerable host forests three or four decades down the road. They postulated that the utilization practices of the day tended to encourage the succession of even more fir, the key problem species, the prospects were of major importance to the then-burgeoning wood-fibre industry. This advice provided convincing support for the establishment of the Canada-wide Forest Insect Survey in 1936 and a forest entomological research establishment of the late 1940s and 1950s that may never be surpassed in its strength or dedication to the fundamentals of forest insect population dynamics and to mitigating pest problems through natural control factors and evolving biological controls. The work of this establishment found expression in a number of notable efforts - intensive field studies of the budworm's biology and impact in northwestern Ontario and Quebec, of its population dynamics by the Green River Project in New Brunswick and the establishment of the Insect Pathology Laboratory at Sault Ste. Marie. Outbreaks of the 1940s in Ontario and Quebec also encouraged cooperative dealings with US Department of Agriculture of the most practical forest insecticide, DDT, and led to the establishment of the Chemical Control Research Institute in the 1950s, later to be amalgamated with the Insect Pathology Research Laboratory as the present Forest Pest Management Institute.

Thus spruce budworm monitoring and evaluation techniques originate from three basic needs in Canada: (1) those of the national Forest Insect Survey for very extensive annual surveys of population levels, natural controls and damage; (2) those of fundamental investigation of the budworm's biology, population dynamics and interaction with its hosts; and (3) to service the needs of insecticidal control projects.

Methodology for very extensive surveys is in many ways the least demanding. The product has important broad scale inter-provincial application and is basic to research of long-term outbreak and damage history. Much of present methodology still dates from the earliest survey days - observation reports, beating sheets, 45 cm branch tips, binocular examination of defoliation in tree crowns, aerial sketch mapping etc. Recent emphasis has been placed on evaluating impact, so far without particularly notable results. Except in Quebec, which provides this information to the national survey, this is almost entirely a federal responsibility of the Canadian Forestry Service with various degrees of field assistance provided by the provinces and industry.

The second need was the second to arise - that of intensive, fundamental field research usually at pin-point locations. It is exemplified best, perhaps, by the life-table methodologies developed by Morris and his colleagues of the Green River Project in New Brunswick in their analysis of the population dynamics of the insect and of its interaction with its hosts and environment. This narrower focus lends itself more readily to the development of scientifically verifiable data and statistical manipulation, but is time-consuming and expensive. For practical purposes it is a need primarily of fundamental research and therefore primarily of the CFS.

The third and most pressing recent need is that of the forest manager and the applied protection practitioner and lies between the first two in its demands for geographic coverage and statistical exactitude. It also features a number of other characteristics. It demands the ultimate in prompt reporting. In New Brunswick it has provided the driving component of the predictive simulations of budworm/forest/imposed protection interactions and budworm management modelling. It involves varying degrees of provincial self-reliance in carrying out the surveys depending upon their intensity and the importance of the problem in the separate provinces. Quebec's self reliance is virtually complete while New Brunswick's and Newfoundland's are largely so. In the remaining provinces, where the scale of applied protection remains relatively low, and the size of the job remains within the CFS capability, reliance has continued to be placed principally on federally-conducted surveys.

Methodologies for this third purpose lie somewhere between the first two in their scientific sophistication and amenability to statistical treatment. A major boost was provided to their development 30 years ago by Morris and Waters who almost simultaneously demonstrated the adaptability of sequential sampling for such middle-scale assessment needs. This method of anticipating defoliation from egg counts was combined with weighted assessments of three parameters of existing tree condition obtained by ocular estimation to develop the Webb *et al* hazard index introduced in New Brunswick in 1955. Surprisingly this model and its weighting remain, with mostly minor variations, the state of the

art in forecasting hazard for planning protection throughout the Atlantic Provinces and Maine. Borrowed briefly in Quebec it was supplanted some years ago by one considered to be more sensitive to protection strategies and tactics there. The validity of the New Brunswick model, particularly in terms of measuring the ability of present-day trees and stands to withstand further stress is increasingly coming under overdue examination in New Brunswick and elsewhere. The washing technique and L₁ larval sampling techniques pioneered by Miller and Kettela in the early 1970s are believed to provide more sensitive forecasts of damage and have become a regular adjunct to conventional egg counting methods. Various attempts have been made to improve the sophistication of aerial surveys but these will probably remain essentially primitive in nature until remote sensing technology advances sufficiently to replace direct ocular estimation.

As I stand back and look at this history and the state of affairs in the windup years of CANUSA I am left with certain convictions, two or three of which I offer here.

First and foremost I find it difficult to recognize that the development of methodologies for monitoring and evaluating the budworm and the budworm problem over the past quarter century in Canada has been in any way commensurate with the need. Even allowing for what are termed "new and improved techniques" at this workshop, and the increasing swing of very recent years toward recognizing the problem as more of a forest management one than an entomological one, surveyors and assessors really have very little more or better methodology at their disposal than they did that long ago. Even with the equity that I have in some of that old stuff I cannot regard that as a satisfactory record.

There is a relationship, I suspect, between this and my second conviction. It is that on the Canadian side certainly, the CANUSA concept of a "user" community is confusing if not confused. For if one tracks the methodology "user" to his lair in most of Canada it usually turns out that he is from the very agency expected to develop that methodology; in short in more cases than not the CFS is playing the role of both developer and surrogate user. Except in Quebec, the design of by far most surveys and assessments for budworm management in Canada is left by forest managers to CFS advisors, the former often being only vaguely interested in the systems employed on their behalf.

This is not a criticism of the CFS. It is simply a statement of a situation that exists, and a partial explanation of my belief that there is really not much of a Canadian audience out there just now for the sort of Users' Manuals that CANUSA seems to have had in mind, unless it is to facilitate technology transfer within the federal establishment itself. Neither are my remarks intended to discourage state of the art and accomplishment reporting by CANUSA, but rather to discourage a misconceived approach to

it. If I do have any criticism it is that the forest management agencies, i.e. the provinces, excepting Quebec, and the forest industry in Canada have shown too little interest in managing their budworm surveys and assessments themselves, of being too willing to accept a surrogate. Until this changes, it does not seem to me to be possible for them to demonstrate that they have their management responsibilities firmly in hand and that the accountability they have for that management can be properly provided.

Finally, if you will accept my argument that to a large extent the CFS is not only the principal producer of methodology in Canada but the main "user" as well, it might be appropriate to examine the effectiveness of producer/user interaction in that arena. To what extent, e.g. does the Forest Insect and Disease Survey get assistance in the development of better methodology from the more fundamental budworm research community? Evidently not a great deal in the past 30 years. The Green River project invented the branch surface-area unit for egg population expression, and a prototype egg-sampling table, but a CFS user-surrogate (in the person of myself in the 1950s) translated these into the subsequently-used tables and coupled this with tree condition to produce the long-lived empirical hazard model referred to already. In fact, in New Brunswick almost every piece of monitoring and evaluating methodology that has stood the test of time for planning and evaluating spraying programs has originated from CFS user-surrogates. In recent years Forest Protection Limited and the New Brunswick Department of Natural Resources have begun follow Quebec in developing methodologies for their special needs, notably computerized mapping of egg, hazard and vulnerability data.

In summing up I do not expect much argument that present methodologies are weak and short on definable statistical integrity. The concept of a producer/user breakdown for methodology use, as may be appropriate in the US, is at present largely illusory in the Canadian context, due in large part to insufficient assumption of the "user" role by the real resource managers except through a surrogate system. Finally, the institutional compartmentalization of the federal research/advisory service may be standing in the way of a sharp focus on methodological development for any of the three broad needs that I have identified. CANUSA might have stood a better chance of optimizing its effectiveness on the Canadian side had these realities come into clearer focus earlier.

For the sake of argument.

INTRODUCTION TO WORKSHOP ON "NEW AND IMPROVED
TECHNIQUES FOR MONITORING AND EVALUATING SPRUCE
BUDWORMS"

Bradford Walker

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and Recreation, Agency of Environmental
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It is of considerable personal pleasure for
me to have the Vermont Division of Forests
sponsor this workshop for the exchange of
information on budworms, for I served on the
CANUSA Joint Planning Unit for several of the
early years of the program. I was, and remain, a
zealous (if not objectionable) proponent of
making technology transfer a final integral phase
of the CANUSA program.

Being a new home for the budworm, Vermont is
the new kid on the block, so has a lot to learn
about the idiosyncracies of the beastie. By the
same token, however, we have the advantage of
learning from the experience of other budworm
battle veterans. Fortunately, much public
interest in the spruce budworm problem has
developed in northeastern Vermont on the part of
private forest landowners, pulp cutters,
consulting foresters, town officials, and
legislators in the infested areas. Opposition to
the use of chemical insecticides presents a
difficult climate for carrying out direct control
with anything but B.t., but this has proved
helpful in gaining considerable support for a
multicultural approach to control through
integrated pest management techniques. The last
state Legislature appropriated (during hard
economic times) special funds to initiate an
integrated budworm management demonstration
program supported by cooperative U.S. Forest
Service funding. All we have to do now is make
the budworm read our book and be manageable.

Either way, all of the subjects on the agenda
of this workshop are especially timely for us here
in Vermont because the sampling schemes are
tailored to our needs in facing a new fast-
developing epidemic evolving from a long-standing,
historically endemic situation. Incidentally,
any of you researchers who have money and will
travel, Vermont presents an ideal opportunity to
study the insect in the initial stages of problem
development.

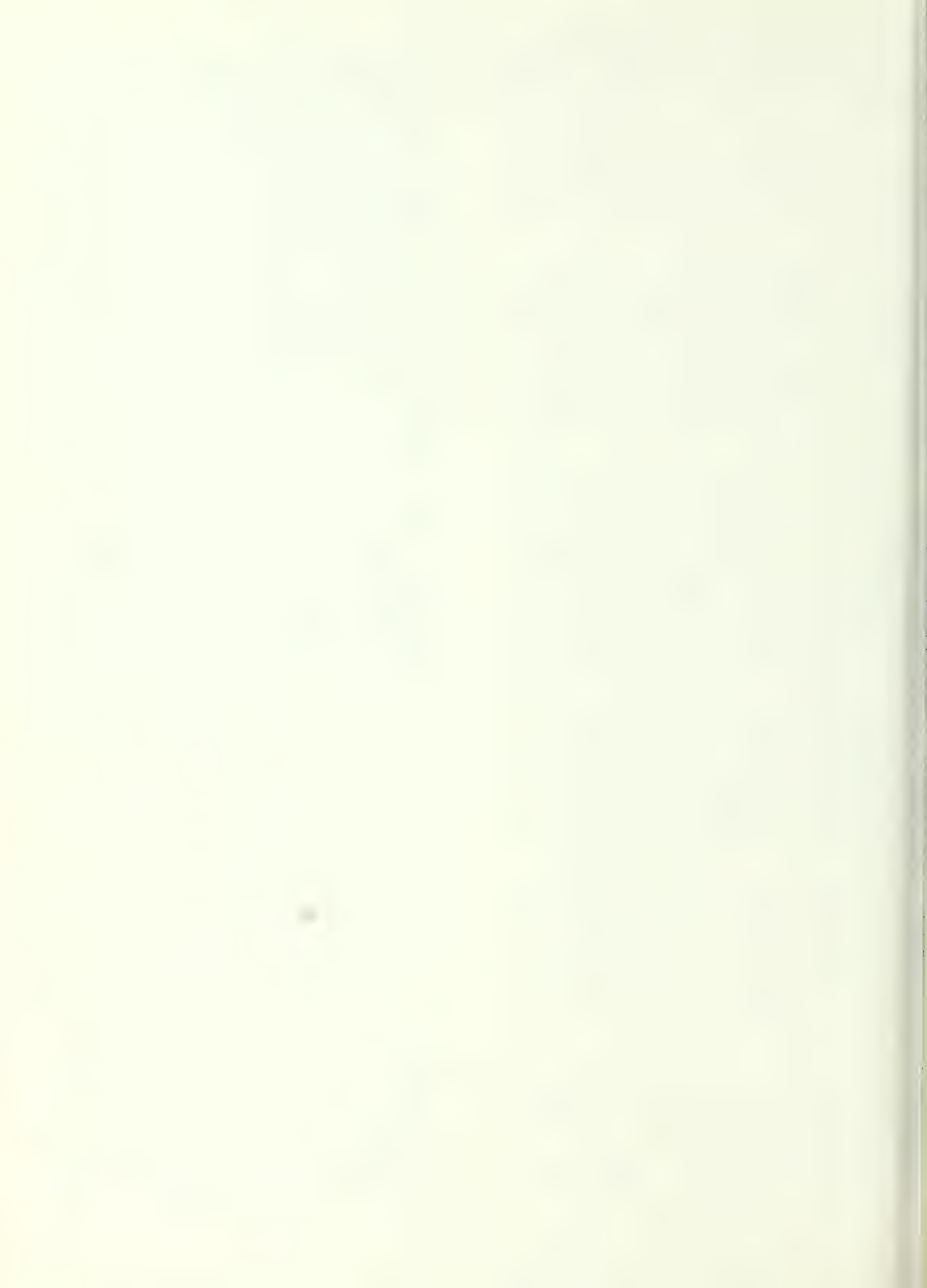
Indeed, not only we in Vermont, but all who
battle the budworm, can benefit from new and
improved techniques for monitoring and evaluating
spruce budworms on an ongoing basis, not simply to
prepare for future outbreaks, but to better
understand and manage budworm populations on an
integrated pest management basis. Forest managers
need to gain "a working knowledge of natural

numerical regulation . . . and particularly the
identification of existing limiting density
factors." With such knowledge, "treatments
should no longer be applied blindly according to
type procedures inherited from the past or other
disciplines but be made to conform objectively
with the forest ecosystem, local circumstances,
and the future. Suppression of intolerable
populations (whatever the criterion) is the
ultimate consequence of comprehensive husbandry
based on sound ecological fact and theory. The
integrated control concept is the embodiment of
this philosophy." I wish I could take credit for
these thoughts, but Geier and Clark beat me to it
back in 1960 in "An Ecological Approach to Pest
Control"; and Ron Stark reiterated them at the
Third Annual Northeastern Forest Insect Work
Conference in 1970. Stark summarized his paper
on "Integrated Control, Pest Management, or
Protective Population Management?" by saying:
"Although great creative effort will be necessary,
[this approach] should prove to be less costly,
invoke less social and ecological repercussions,
and be of more lasting benefit than the continued
use of present-day methods which ignore the
ecological realities of pest regulation."

Ron concluded his talk with
"Let us take heed!"

With this workshop, it appears we are on
track. Continuing low-, medium-, and high-level
monitoring on an ongoing basis using new and
improved techniques, should provide the basic
information needed to formulate and conduct a
long-overdue, truly integrated, pest management
program for spruce budworms--

and, at long last, we are indeed taking heed.



ENDS?

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The three reasons why we should monitor
spruce budworm population trends are to
provide information for further research,
manage spruce budworm, and 3) record
historical data.

There are three basic reasons why we should
monitor spruce budworm population trends. They
are: to provide information for further research,
manage the biological and economic values of
the fir-spruce resource, and to record budworm
infestation history.

Research scientists use information to solve
problems. Tools, references, and equipment that
they employ to gather such information are an
essential part of research. At this workshop we
will be discussing some of the tools used in
monitoring spruce budworm population trends.
Research scientists may use the information to
solve a number of problems and answer several
questions posed by pest managers. As budworm
population levels rise, can we expect insect
behavior to change? Will dispersal patterns,
feeding behavior, or mating vary with population
levels? If so, how, and what are the implications
for budworm management?

If we monitor spruce budworm population
trends, we can learn something about population
trends of associated plants and animals. For
example, research investigations into budworm
parasites and predators, insects feeding con-
currently with budworm, and seed production
depend upon information about budworm population
trends and numbers.

Budworm population trend data are also
needed for researching correlation of weather
effects on spruce budworms and host trees.
Short term trends between life stages and long
term trends between outbreaks are of value in
addition to trends from year to year.

Monitoring of spruce budworm population
trends is essential to the economic aspect of
pest management. Decisions on what action to
take, if any, are based primarily on budworm
population levels expected in the near future.
Being able to predict budworm population
levels could save us considerable time and
expense, but we need to know trends.

When spray operations are conducted to
suppress damaging budworm populations, we need to
know project efficacy. This knowledge applies
to the current year and to the several years
following an operation. Pheromone traps may be
able to better evaluate spray project results in
the future.

Many people, dollars, and pieces of equip-
ment need to be sent to the right place at the
right time if we are to economically manage
budworm. If we monitor the trend of budworm
populations at all levels of infestation, pest
managers can allocate resources for maximum
benefit.

The proper timing of treatments depends
upon knowledge of budworm population levels. The
earlier in an outbreak we can suppress a popula-
tion, the less costly control will be in the
long run. By knowing the trend of a population,
we will know when to act. Stable, extremely low
populations have a way of rapidly building to
destructive levels. Relying on aerial surveys
to detect defoliation by budworm puts us at
least one year behind in planning and suppression.

Changes in budworm populations may indicate
that a different kind of sampling unit, a
different life stage, or other adjustments in
our management surveys should be used. Economics,
time-frames, available assistance, or type of
facilities may all be involved in deciding which
sampling units and techniques we use.

Trend data collected during an outbreak may
help pest managers predict a crash or collapse of
a budworm population. Once the event occurs,
follow-up monitoring would be needed to locate
relic budworm populations that provide spawn for
future outbreaks. These small relics would be
relatively inexpensive to eradicate. Budworm
populations have different trends in our numerous
small stands in the Lake States. Therefore,
monitoring is needed to delineate the areas of
immediate concern and those where further work
can be delayed.

A third reason for monitoring spruce budworm
population trends is to provide a historical
record. Short term trends of several populations
could be used to predict region-wide trends. The
prediction in turn could aid forest managers and
others in formulating forest plans.

Trend data over the years can be used to
advise political leaders of impending budworm
problems. History of budworm outbreaks and
reliable predictions lead to better political
handling of the budworm problem. Budworm
outbreaks are just one of many factors in the
conduct of political operations and trend data
can put the budworm situation in perspective.

Investigators in biological sciences need to know the history of budworm population changes so they can study other life forms associated with the spruce-fir type. We can save considerable amounts of time and money in the public sector by having trend data available for use by others.

The uses of budworm trend data are many. New uses are still to be found. New tools and methods will help us standardize our units of measure and make reliable trend predictions. Why should we monitor spruce budworm population trends?--so that forest managers, pest managers, researchers and political leaders have the best information on which to make decisions.

TECHNIQUES: WHY?

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A case study of 5 year's effort for standardization of entomological techniques used on large scale forest spraying programs against the spruce budworm, *Choristoneura fumiferana* (Clem.), in the Great Lakes region (Ontario, Quebec, New Brunswick, Nova Scotia, Newfoundland and Nova Scotia) is presented. Differences between techniques used are discussed and approaches promoting standardization are recommended when comparable techniques are suitable.

Introduction

Standardization of entomological techniques is like "Virtue", nobody could be against it but it is difficult to practice it.

The literature regarding techniques is scant; a few publications deal with detailed descriptions, or techniques will be summarized in a chapter being part of the scientific approach, but not the essence of the communication. I think this is right. It is important to describe the method used, but why elaborate on a technique that will be repeated 2 to 3 times?

Meanwhile, the problem is quite different for the spruce budworm requiring each year a tremendous amount of information directly affecting management decisions for different jurisdictions. Techniques then appear to be more important.

The problem of entomological techniques standardization was presented to the Eastern Spruce Budworm Council, who mandated their entomologists to standardize techniques used on large scale spraying programs. The idea was that, even if provinces or states react differently to the budworm problem, the techniques used to make decisions should be similar, or at least comparable, from one jurisdiction to the next (Dorais and Dela, 1982).

Goals and Objectives

As a first step, the entomologists listed existing techniques that were routinely used in the decision making process for recommendation of spraying. The list was as follows:

Pest Infestation Surveys

A. Population surveys

1. egg mass surveys

2. overwintering larvae surveys

B. Damage surveys

1. aerial defoliation surveys
2. ground evaluations of defoliation
3. tree mortality surveys

C. Risk rating

II. Spray Program Evaluations

1. insect and host development
2. larval mortality
3. assessment of foliage protection
4. overwintering larval mortality

The entomologists also agreed that essential to any standardization was a systematic description of techniques used, in order to be able to compare and to point out at what level differences appeared. The points compared were:

1. objectives
2. references in literature
3. area covered and intensity
4. timing
5. field procedure
6. data collection
7. cost
8. interpretation and use of data

Comparison of Techniques

1. Objectives

Comparison of objectives showed a general consensus; entomological techniques are used to evaluate population levels, damage to tree foliage, or treatment efficacy, in order to facilitate spray decisions. In this perspective, techniques selected are those which give the answers wanted; techniques seem to be inadequate when used for any other purpose than the initial objective of spray recommendation. For example, when areas of tree mortality are reported by an aerial defoliation survey and the information is used to plan a salvage cut, then sampling precision is often criticized as inadequate.

2. References in Literature

Techniques used operationally are essentially the same in each province or state and are derived from an original reference in the literature. Good examples are the egg mass survey described by Morris, and the caustic soda larval survey described by Miller and Kettela.

Over time, these have been improved locally for more accuracy or adapted to suit local conditions. These modifications are minor, however, and do not alter significantly the original technique. Standardization of techniques which did not take into account the improvements would be unacceptable and could even be considered as a step backward.

This brings up the point that the first step in standardization must be an accurate, detailed description in a scientific publication; some modifications could then be introduced but at least they would be oriented in the same direction. The absence of careful documentation in the literature is an invitation to very different approaches and the widest variety of data collection methods (example-tree mortality evaluations).

A carefully described survey technique, however, provides the forest manager a tool (guide) that is sufficiently precise to conduct his entomological survey, even though such activities are not the main part of his occupation.

3. Area Covered and Intensity

Some surveys are done for specific needs (example - caustic soda larval survey) but for many surveys all of the spruce - fir forests under management must be considered (example - aerial defoliation survey). Faced with the situation of very large territory to cover and limited funds available, all provinces and states end up with very intensive (expensive) methods for experimental blocks, intensive surveys for high priority areas and extensive surveys where a general evaluation of the infestation is sufficient.

In low priority areas, the intensity of surveys will vary as a function of accessibility; large areas often can not be covered adequately and get minimal coverage by way of a few very expensive plots (helicopter plots).

The intention is to get enough pieces on the puzzle to get the general picture of the situation, but everybody understands that on such a basis the local resolution of the evaluation is poor. Because no spraying is usually anticipated in these areas, the information always seems to be sufficient.

For intensive surveys, the intensity will be a direct result of needs and the precision required vs time and money available. On a statistical basis, intensity itself is hard to

standardize while fluctuating with the stage of development of the outbreak.

Example - patchy situation of early and late stages of the infestation needs more samples than the homogeneous pattern of a wall-to-wall infestation.

Meanwhile, the information required to guide spray decisions is an index of population magnitude plus a standard deviation. The standard deviation of the mean, at that time, more than sampling intensity itself, would be the thing to standardize to get more uniformity on precision of evaluations. Sampling precision is now determined by the money available, allowing for an acceptable minimum based on experience.

($\sigma_{\bar{p}} = 15\%$)

The reliability of data collected for large scale spraying programs is considered as acceptable by jurisdictions to make good decisions for spraying, but is definitely not sufficient to plan each result at the stand level, such as experimental blocks with special requirements for very good statistical precision. ($\sigma_{\bar{p}} = 10\%$) Higher precision is always possible, but that will not improve the actual result. Standardization of precision is not recommended as long as the minimum acceptable is adequate to meet needs.

Intensity of sampling in insect development plots in another story and varies with the tree phenology and stand composition of the area. Highly homogeneous areas won't need as many plots as mountainous ones and the intimate knowledge of the area by the field technician will result in cost and time savings. The same thing could be said for stand composition, where insect development varies between host species; a pure fir stand won't need as many samples to time spray operations as a mixed fir - white spruce stand. Standardization then has to be subordinated to the judgement of field personnel which appears to be the key factor for timing of sampling development plots. The practice of dividing the territory into smaller areas, with each small area re-evaluated by the same person, provides a lot of advantages and seems to be more and more popular in the different jurisdictions.

To standardize intensity of sampling appears to be sometimes not desirable and sometimes unrealistic. The precision of sampling in large scale spray programs must be considered acceptable based on a minimum of information required to make good decisions regarding spraying. Standardization is recommended as long as the minimum acceptable precision is attained to meet needs.

Example - Aerial defoliation surveys in Brunswick are flown along lines 3-5 km apart, covering all the province. This is not done in Ontario or Northern Quebec which present a more patchy pattern of host type than in New Brunswick.

Timing and Field Procedures

Usually, evaluations are timed according to development of the insect or phenology of the host tree, except for tree mortality evaluations, which could be done at anytime during the year but preferably not during the "browning" period.

Field procedures are similar from one province or state to another, except for the ground surveys (defoliation and egg masses) where the long-standing controversy of field vs lab examination arises. Evaluations could be done in the field or in the lab, depending on approaches taken and the facilities available, without that much difference, but a central laboratory seems to be favored when a massive project is required. The lab then allows for better control and uniformity of results.

Data Collection and Cost

Activities such as this meeting, having people involved in sampling described and rationalize their routine operational exercises, is, per se, very constructive and helps to standardize data collection.

Example - Branch measurement for egg masses survey could be done in various ways when not described in detail.

Pictures and color slides shared among evaluators doing the same job in different jurisdictions have been found to be a very good tool to help standardize data collection, especially when the information required is not quantitative.

Example - Bud index, L_2 larvae on filter paper, and insects other than budworm encountered on sample branches.

Having techniques well described and illustrated will improve uniformity, especially when examinations of sample branches each year are done with inexperienced workers. In such a situation, the experienced lab technician will be able to present things in easily understood language.

Uniformity of data collection between jurisdictions can not be complete without considering representativeness; that is, field techniques could present an objective local evaluation or a large-scale subjective evaluation.

Example - Fettes method vs field-glasses evaluation of annual defoliation.

Both techniques are used, but which one is the best? Each of these techniques has its place, depending upon the goal for the spruce budworm evaluation. The first one (Fettes) is directly associated with larval mortality and is needed to complete the treatment efficacy picture in terms of branch defoliation, while the latter method (field-glasses) allows for wider coverage and is used to validate the aerial evaluation of defoliation.

The degree of conformity between these two different evaluations will be directly related to the homogeneity of the area studied and to the skill of the field technician in finding trees which are really representative of the area evaluated. Once again, it seems that standardization must be subordinated to the judgement of the experienced field technician, who after must assist the entomologist with only a minimum of resources.

Survey costs, reported per plot or per km^2 are in the same way related to facilities available. As always, cost per plot is reduced when large numbers of plots are examined. (Example - L_2 caustic soda larval survey).

6. Interpretation and Use of Data

Comparison of techniques shows that results are presented using the same categories or same sample units in all jurisdictions.

Example - Light, moderate and severe defoliation categories. Number of larvae per 45 cm branch tip.

Still, some differences exist in defining limits of the categories, where the interpretation, per se, in terms of impact on the tree is not documented precisely enough to clearly specify the border lines.

Example - Defoliation is considered moderate when between 35-70% in Quebec and between 26-65% in New Brunswick.

On the other hand, the risk rating map, derived from a summation of all data collected, is based on four categories essentially identical everywhere and spray recommendations based on those categories are the same as well: no spray recommended for the low category, but spray considered for the others. The only grey area that persists at this time is the cut-off point at which time a forest is considered already too damaged to be sprayed.

Conclusion

We can't expect to have things done (budworm sampling) exactly the same way all over northeast America, but up to a certain degree the approaches and techniques used are already standard from one province or state to another. Differences pointed out are minor and were made to improve the original technique or to suit local conditions; further standardization would not be acceptable if those minor improvements were not retained.

Techniques now in use seem to meet the original goal for which they were developed. The intensity of sampling sometimes differs, but seems to meet the needs, considering the money available and variations in forest composition or geography. Once again, standardization is sometimes unacceptable.

able and sometimes must be subordinated to judgment of experienced personnel in the field.

In the long run though, frequent contacts between people involved in sampling and discussions of problems encountered appears to be the ideal way for movement toward standardization of techniques, which has to be considered, as "Virtue", the long term goal.

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Dorais, L. and E. G. Kettela, 1982. A review of entomological survey and assessment techniques used in regional Spruce Budworm, *Choristoneura fumiferana* (Clem.), surveys and in the assessment of operational spray programs. Report of the Committee for the Standardization of Survey and Assessment Techniques to the Eastern Spruce Budworm Council.

by A. Simmons and Norman C. Elliott

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Predicting the timing and occurrence of forest insect infestations and outbreaks has long been a goal of many forest entomologists. Analyses of yearly light trap catch totals from Maine showed that population surges of budworm were indicated four to seven years before defoliation was first observed. In this paper we discuss how such trend information can help predict infestations or outbreaks of spruce budworm.

Idea Behind Trend Information

Spruce budworm populations persist at low densities until the forest ages sufficiently to support higher populations. These fluctuations occur at irregular intervals, ranging from 20 to 90 years in individual stands. Three possible conditions can "release" the population to high densities: (a) weather conditions bring budworm populations but not favoring natural enemies of the budworm, (b) migrating budworms laying eggs in numbers such that natural control factors cannot keep the budworm at low numbers, and (c) a combination of the above. Regardless of the cause, the population fluctuation for budworm over time follows an "S-shaped" curve (Fig. 1).

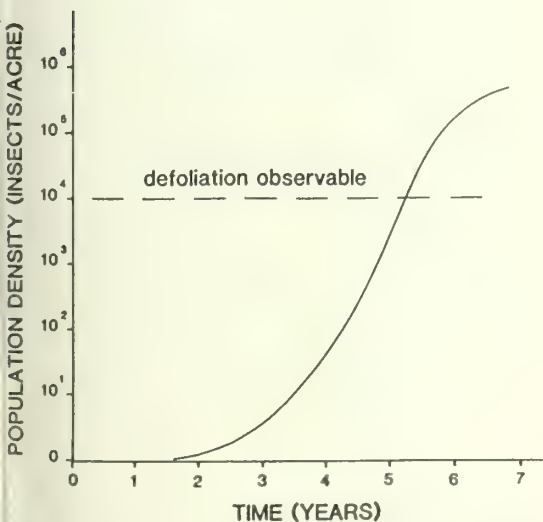


Figure 1. Fluctuation in the density of a hypothetical spruce budworm population over time.

The point on the graph where the curve turns upward from low density is when the "population release" occurs. From this point on budworm populations

will continue to rise to a high level. Theoretically, this "population release" point occurs several years before budworm populations are high enough to cause noticeable damage.

By using light traps or pheromone traps (Simmons 1980), which measure budworm populations, this population release can be detected. To do this, place a trap at the same location over several years; plot catch totals on a graph. The graph should pinpoint "population release" for that location.

Analyzing Actual Trap Catch Trends

A plot of yearly light trap catch data, taken at Eustis, Maine, from 1962 to 1974, is shown in Figure 2. From 1962 through 1966, no moths were caught--establishing a trend of very low (undetected) populations. In 1967, three moths were caught, and in 1968, nine moths were caught. The 1967-68 period is the first upward trend in the plot--the "population release" point. From 1968 onward, all captures exceeded ten moths per year indicating a rising trend to a high population. Noticeable defoliation was recorded for the first time in 1974. If 1968 is the first year of the rising trend, there were six years before defoliation was first observed at Eustis.

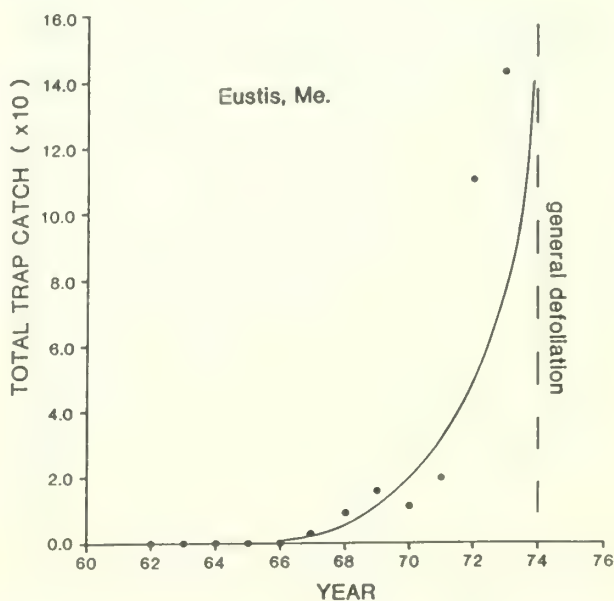


Figure 2. Yearly light trap catch totals, taken at Eustis, Maine, from 1962 to 1974.

Operational Use of Traps

Actual trap catch information, such as that just described can be used in regular forest management operations. One of the first steps would be to organize the forest area of concern into smaller management units. In the Lakes States Region, these units are often termed "compartments." These are parcels of forest land from 1,000 to 3,000 acres. Within the compartments are usually several timber types, sometimes including a few to several individual stands of spruce-fir.

The next step is to determine which compartments have stands of spruce-fir worth managing. Those compartments containing stands of sufficient value to be of concern should be located and noted. Compartments containing no spruce-fir would not be considered.

Within each compartment containing spruce-fir of value, stands should be rated (hazard rating) for their potential to sustain damage from spruce budworm if an infestation or outbreak should occur. Compartments containing high hazard stands would be the target of trapping to help predict damaging populations of the spruce budworm.

Two approaches to monitoring low spruce budworm populations could be employed: (a) a "lower precision" approach that monitors only the compartments of concern and (b) a "higher precision" approach that monitors every stand of value at risk within every compartment of concern. The "lower precision" approach would use one trap in one high hazard stand in each compartment of concern, providing a general monitoring station for the entire compartment. The "higher precision" approach would use one trap in each high hazard stand within every compartment of interest, thus providing multiple monitoring stations within a compartment (unless only one stand was considered high hazard).

The advantage of the lower precision approach is that fewer traps are required per compartment, thus reducing the cost of monitoring. The disadvantage is only one stand is monitored and that information might not represent what is happening in every high hazard stand in the compartment. An alternative is to use one trap in homogeneous compartments while deploying multiple traps in more heterogeneous compartments.

When Is This Approach Appropriate?

In areas where budworm is "always a problem" or in areas that have been repeatedly sprayed for budworm, the methods described herein will not give you more than seven years of lead time before tree damage occurs. There may be some lead time, but damage could also occur within a year or two. This approach works best when populations of the spruce budworm are usually low and unnoticeable for many years, erupt to outbreak for a few years, then return to low and unnoticeable for many years.

What's Best to Use: Light Traps or Pheromone Traps?

When we conducted our studies, the only long-term data sets available were from light trap catches. Assuming that pheromone traps are at least as sensitive as light traps in detecting population change, pheromone traps are probably a better tool than light traps. They cost less individually, are easier to transport and deploy, and most importantly, are selective in attracting spruce budworm moths. Light traps attract all kinds of insects, requiring the catches to be sorted by entomologists and necessitating the traps being tended every few days. Pheromone traps can be left for the entire moth flight season, then retrieved, with the counting done by non-entomologists.

Our suggestion--use pheromone traps!

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APPLICATION OF PHEROMONE TRAPS TO EFFECTIVELY
MONITOR SPRUCE BUDWORM POPULATIONS

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Non-saturating traps baited with synthetic sex pheromone can effectively monitor spruce budworm populations. Presently available traps, and possibly the lure, need further improvements in order to provide a commercially available combination in which field personnel will have confidence. A standardized protocol will be essential for implementing a pheromone trapping system.

Preliminary results from extensive field trials in Canada and the United States during the past three years indicate that a non-saturating trap baited with synthetic sex pheromone offers forest managers and pest survey specialists a relatively inexpensive and reliable way to monitor populations of spruce budworm (*Choristoneura fumiferana* (Clemens)). The sex pheromone used was a 97:3 to 95:5 blend of E- and Z-11 retri-decenal (Sanders and Weatherston 1976, Ramaswamy and Carde 1982). The E:Z ratio varies among commercially available lures. Ample evidence was accumulated during the last five years to demonstrate that traps baited with synthetic sex pheromone catch male moths in numbers that can be related to budworm larval density. Research in Michigan (Ramaswamy and Carde 1982, Carde 1983), Canada (Sanders 1978, 1981; Sanders et al. 1983) and the CANUSA-East field trials in Quebec, Newfoundland, Maine, New Hampshire, Vermont, New York and Michigan, produced meaningful trap catch correlations (r^2) of 0.76 to 0.95 with 3rd (3L) and 4th (4L) instar larval counts of the same generation and with 2nd (2L) instar larval counts of the next generation in sparse to moderate populations. Very promising results have also been obtained at higher population levels.

If the results of the 1983 CANUSA-East field trials corroborate earlier work, we may be able to utilize pheromone traps operationally in the near future. It is anticipated that a properly deployed trapping system will provide an early warning of impending outbreaks in low population areas where other forms of sampling are expensive, time consuming, or logistically unreasonable. Hopefully we may even be able to supplement other sampling procedures routinely used in high populations such as egg mass or overwintering (L2) larval surveys.

The covered-funnel trap (CFT), a non-saturating model developed by Ramaswamy and Carde (1982) and slightly modified by us (Fig. 1) is presently our standard trap. A recent trap design by Sanders (Sanders et al. 1983), called the double

funnel trap (DFT), also performed to the same degree as the CFT trap. Additionally, a commercially available plastic canister gypsy moth trap, modified for use in the CANUSA trials, also appears promising. However, as you will hear tomorrow, additional improvements will be necessary before we have a "standardized commercial trap" that we can recommend with confidence.



Figure 1. Covered-funnel trap (CFT), the standard non-saturating trap used in CANUSA-East field trials.

The CANUSA project used two commercial lures; the Hercon® (Health-Chem) Luretrap®, a 1/2" square plastic laminated sandwich impregnated with a 95:5 blend of E- and Z-11-tetradecenal and the Conrel® (Albany International), a white celcon hollow fiber containing a 94:6 blend of E- and Z-11-tetradecenal. Both gave good results in the 1982 CANUSA field tests and in Sanders'¹ 1982 lure evaluations. However, until our 1983 results are analyzed and compared to those from Canada, we cannot recommend either one. Our intent is to

obtain a consistent pheromone release rate and develop a trapping system that reliably correlates moth catch with larval budworm density.

The present trap, and possibly the lure, need further improvements in order to provide commercially available combination in which field personnel will have confidence.

Results of the 1983 CANUSA-East field trials will tell us if we are ready to start the development of regional budworm monitoring systems using pheromone-baited traps. Recommendation for a pheromone trap monitoring system will be presented tomorrow. One of the most important aspects of monitoring with pheromone traps is standardization of not only the trap and lure but also a protocol to implement the system. Without standardization the system will provide limited opportunity to apply results and improve the technique. Careful organization and planning during the early stages of development will increase the opportunity to produce a monitoring system that is applied in a standard fashion at all agencies.

The three years of CANUSA-East field trials with pheromone traps have shown that data inconsistency was due, in part, to the fact that crews did not follow standard protocol. This lack of conformity resulted from inadequate clarification and demonstration of methods. Part of the problem can also be attributed to a propensity for field personnel to "do their own thing." Following is a basic framework from which we can develop a standard procedure for application of pheromone traps within regional pheromone monitoring systems.

TRAP: A standard non-saturating trap should be approved by all participants in a monitoring system. The trap must be commercially available, durable, and easy to assemble. It must retain numbers of moths that consistently reflect changes in population density.

LURE: A reliable commercial lure that releases pheromone for a specified time at a desired rate is essential. The lure must be positioned within the traps in such a manner that pheromone release is not obstructed (Fig. 2). Lures must be stored in a freezer within their original wrapping until taken to the field. Lures are placed in the traps when traps are deployed, approximately one week before flight begins. "Aging" is necessary to avoid field exposure to the adults during the initial burst of chemical that is characteristically released when a bait is taken out of storage.

TRAP PLACEMENT: Traps should be suspended vertically 1.5 m above the ground and attached to a branch on a host tree (if possible) (Fig. 3) or a non-host if the latter is more convenient. The trap should not be closer than 0.3 to 0.5 m to the trunk of the tree. When placed immediately adjacent to the trunk (Fig. 4), air flow is obstructed and traps may become wind battered. Foliage and branches must be removed from the vicinity of the trap (0.5 m clearance) so

¹ Personal communication, C.J. Sanders, Canadian Forestry Service, Sault Ste. Marie, Ontario.

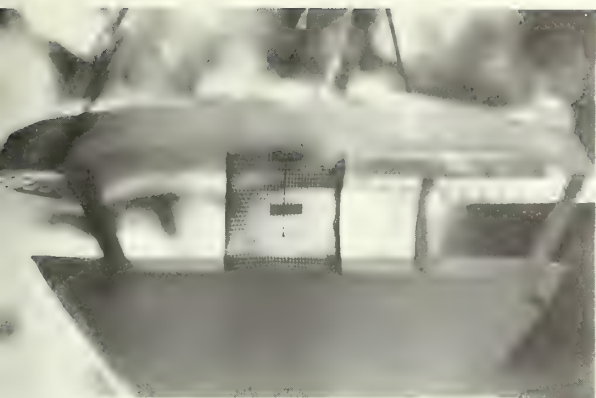


Figure 2. A commercial lure properly positioned within the CFT trap.



Figure 3. A properly placed plastic canister gypsy moth trap, modified for use in the CANUSA-East trials, correctly suspended to a host tree branch.



Figure 4. A CFT trap placed too close to the tree trunk where air flow is obstructed and the trap could be damaged by the wind.

that moth flight will not be hindered. Traps placed along road corridors should be positioned so that the traps are at least 5 m into the host type.

TRAP PLOTS: A plot consists of one five-trap cluster, however, a three-trap cluster is adequate in locations where interference from bears or people is not a problem. Traps should be placed 40 m apart, one in each cardinal direction around a center trap (Fig. 5). The three-trap cluster can be placed in any triangular configuration as long as a minimum of 40 m is maintained between traps. Baited traps should be placed in the field 5-7 days before moth flight begins and remain in the field until adult activity ceases. The total duration of the field exposure of traps is 5 to 6 weeks.

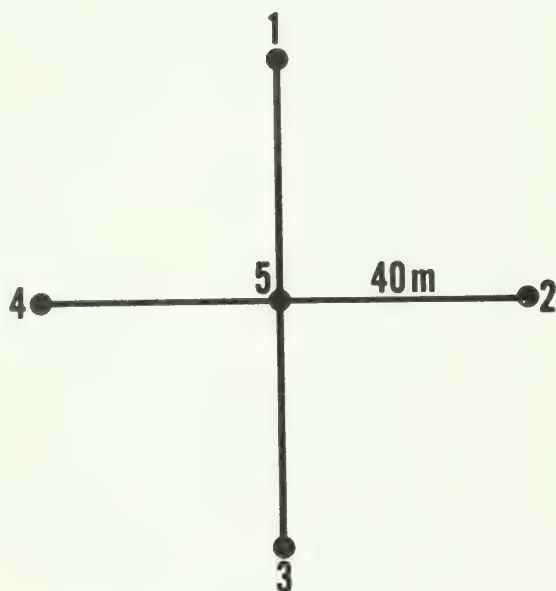


Figure 5. The five-trap cluster used as a plot design in the CANUSA-East trials.

DATA COLLECTION: Male moths should be counted soon after the traps are collected. Small numbers (less than 50) can be counted by hand while larger quantities will be estimated by a weighing procedure that we are developing this year in cooperation with Luc Jobin, Canadian Forestry Service, Quebec. Moth numbers should be recorded on standard forms and data sent to centralized collection centers for regional reporting and statistical analysis.

These are some of the more important aspects of our standardized protocol that must be considered when pheromone traps are used for regional surveys of spruce budworm. We must also recognize that these pheromone traps are not a panacea, but they will provide a valuable monitoring and survey tool within an integrated pest management approach.

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Sex pheromone traps for spruce budworm were originally envisioned as tools for providing an 'early warning' of outbreaks. While there is no doubt they will be effective in this role, the advent of practical, low-cost, "high capacity" traps raises the possibility that pheromone traps could replace more costly sampling techniques, such as egg sampling. A 'home-made' double-channel trap design has given correlations between trap catches and larval densities with r^2 up to 80%. Limited trials with commercial trap-designs indicate that several designs may be suitable for operational use, but more testing is required before a long-term program using a standardised trap design is begun. Similarly, while several types of lure are adequate for the purpose, further testing is required to determine which is the 'best'.

Introduction

Sex pheromones are chemicals released by one sex to attract the other sex of the same species for the purpose of mating. In the case of the spruce budworm, as with most other Lepidoptera, it is the female which releases the pheromone, and the male which responds. When ready to mate, the female spruce budworm everts a special gland at the tip of the abdomen which secretes the pheromone. The pheromone plume is wafted downwind, and a receptive male on perceiving the pheromone, flies upwind towards the source. On arrival he searches for the female and mating takes place.

Most, if not all, sex pheromones of the Lepidoptera are blends of several chemicals. In the right combinations and at the right concentrations, these blends are extremely species-specific as indeed they must be to prevent females from attracting the wrong males. This is one of their advantages as a sampling tool--only the target species is involved. Pheromones are also extremely potent; while it is probable that the effective range of the pheromone is less than 1 km, only a few milligrams are necessary to attract males for weeks, and this is a second advantage--they are extremely efficient.

The main component of the spruce budworm pheromone was identified in 1971 (Weatherston et al. 1971), but early trapping results were disappointing and it was subsequently found that a minor component was missing (Sanders and

Weatherston 1976). With the addition of this it is now possible to produce lures which attract more males than a virgin female moth can (Sanders 1981). The synthetic pheromone is now readily available commercially for a few dollars per gram. This may sound expensive, but when it is remembered that only a few milligrams are necessary to bait a trap, the cost per trap is negligible.

Now that we have virtually unlimited supplies of the synthetic pheromone, what can we do with it? First, it can be used to disrupt the natural sequences of mating behavior to preventing successful mating, thus regulating populations. This has turned out to be a tricky research problem, but is not of concern here. Second, the pheromone can be used to lure the male moths to traps, where they can be captured and counted.

In some ways sex pheromone traps are similar to light traps, they efficiently attract and capture individuals of the target species so that they can be easily counted. The great advantage of sex pheromone traps over light traps is that they are species-specific, inexpensive and simple to operate--no power source is required.

But, before proceeding any further, it is very important to be quite clear of the objectives of trapping the spruce budworm, since traps have been used for a variety of purposes with other insects and the optimum trap design varies with the purpose.

a) Mass Trapping

Traps can be used to catch and remove males from the population. If the baits are potent enough and there are enough traps, sufficient males can be removed to reduce the mating success of the females. Although this has been demonstrated as a practical proposition for some agricultural insects it is not practical for such a numerous, widespread insect as the spruce budworm.

b) Timing of Control Operations

Since pheromone traps are very efficient, they can be used to find out when the first moths fly, and, again in some agricultural situations, this can be used to determine when insecticides should first be applied. Also, for some agricultural pests, notably in orchards, pheromone traps have been used to indicate when it is necessary to spray--when a certain threshold number is reached, the pest has reached economically serious levels.

c) Detection

For migratory pests, or introduced pests which are extending their range, such as the gypsy moth, pheromone traps are an efficient

method of establishing if the pest is present, indicating whether or not more intensive sampling is necessary.

d) Monitoring Population Changes

Finally, we come to the primary purpose for which traps are being used for spruce budworm, to monitor annual changes in population density to provide an "early warning" of impending outbreaks.

For mass trapping, timing of treatment, and detection, highly potent baits are required. For mass trapping, traps must be of large capacity, and their efficiency is measured by the number of insects caught. For detection and timing, efficiency is measured by the ability of the traps to capture the first moths to appear; for detection numerous low cost traps are required, for timing of treatments fewer traps are required, so they can be more elaborate and costly.

For monitoring population fluctuations high efficiency of capture is not necessary and may even be a disadvantage--too many insects in a trap take too long to count. The chief attributes required for monitoring spruce budworm populations are:

- i) Catch correlated with population density,
- ii) Durability over 6-week period,
- iii) Convenience,
- iv) Cost,
- v) Constant capture rate,
 - a) for 6-week period,
 - b) from year-to-year.

These attributes are affected by both the trap design and by the formulation of the lure.

Let us first consider the trap design.

Trap Design

a) Early Tests

When development of the spruce budworm sex attractant for monitoring population changes began in the mid-seventies, the traps available were mostly of a sticky variety. The non-sticky traps which used an insecticide to kill the moths were generally too bulky and too expensive.

Comparative tests of the sticky traps available at this time led to the conclusion that the Pherocon 1CP (Fig. 1) was most appropriate (Sanders 1978). Its design kept the accidental capture of non-target insects to a minimum, and it proved to be durable enough to remain effective 12 months. It was recognized early on that there is a problem of 'saturation'--the sticky surface becomes so covered in moths and scales that incoming moths escape--but, it was hoped that this could be overcome by reducing the potency of the lure. Early trials with the 1CP traps did in fact give reasonable correlations between moth catches and larval densities. Then, in 1980, the Michigan State University group

designed a non-sticky trap (Fig. 2) which was larger and no more expensive than the sticky traps (Ramaswamy and Cardé 1982).

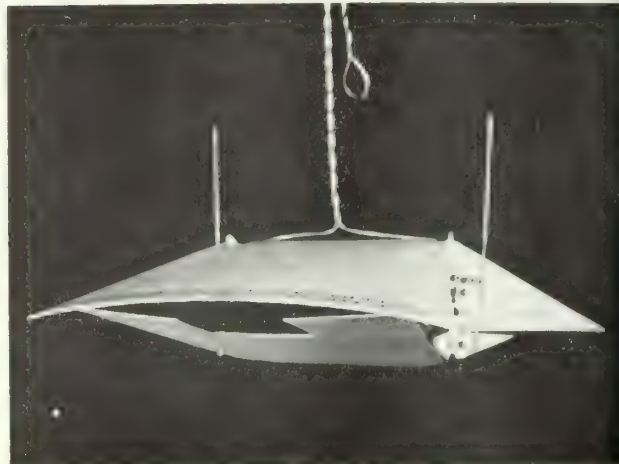


Fig. 1. Pherocon 1CP sticky trap. Only the inside of the lower half is coated with sticky material.



Fig. 2. Different designs of 'non-saturating' traps in which moths are killed by insecticide vapor. Top, 1. to 3. Health-Chem gypsy moth canister trap; International Pheromones Ltd. Uni-trap; Covered-funnel trap. Bottom, 1. to 3. Health-Chem gypsy moth 'milk carton' trap; Baker Chemicals "Bag-a-Bug" trap; Double-funnel trap.

b) 1981 Tests

Tests in 1981 in Ontario, as well as elsewhere, demonstrated that these traps gave a good range of catches over a wide range of population densities. However, we found the traps inconvenient to assemble and store. Also, water entered the traps causing the captured moths to make counting nearly impossible.

1982 Tests

This led to a new design which we have called the double-funnel trap (Fig. 2) and in 1982 we carried out a test to compare the effectiveness of the Pherocon 1CP, the MSU covered-funnel trap (CFT) and the double-funnel trap (DFT). Twenty-three plots were established in northern Ontario, selected to provide a wide range of spruce budworm densities.

Pherocon 1CP traps were baited with 3 different potencies of lure. At the 2 highest all the traps were saturated. At the lowest also, many of the traps were saturated, but at densities below 2.5 larvae/branch tip the correlation between catch and population density was reasonable with an $r^2 = 61.5\%$ and maximum catches of 36 moths/trap (Fig. 3).

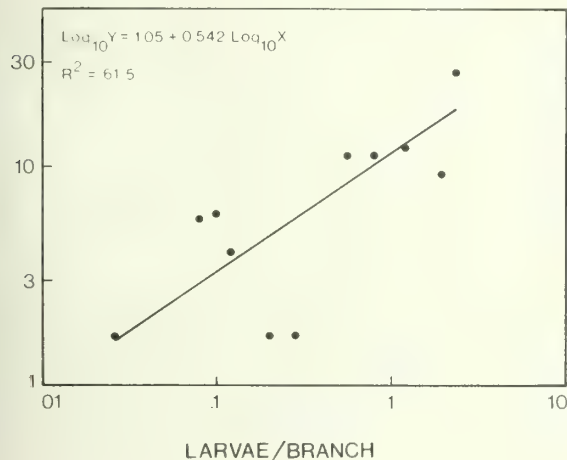


Fig. 3. Relationship between catches in Pherocon 1CP traps baited with low-potency lures and larval density (Ontario, 1982).

Neither the CFT or DFT traps showed signs of saturation, even at the highest population density. For the CFT, $r^2 = 59.0\%$ with catches ranging from 2.6 to 244/trap, for the DFT $r^2 = 76.6\%$ with catches ranging from 18.2 to 670/trap (Fig. 4). In 16% of the CFT traps accurate counting was impossible because the moths had rotted due to the accumulation of moisture which occurred in the center of the modification aimed at preventing desiccation. No such problem occurred with the DFTs.

1983 Tests

In 1983 we again tested the DFT traps for correlations with larval densities. This time we tested clusters of 5 traps and clusters of 3. The correlation between trap catch and larval density was $r^2 = 51\%$ and 49% respectively, poorer than in 1982, but still highly significant. Correlation between the average catch in the 5 trap cluster and the 3 trap cluster was excellent (Fig. 5) $r^2 = 93\%$, implying that a 3 trap cluster was quite adequate. We also tested the correlation between the 1982 moth catches and the 1983 larval density, i.e., the ability of the moth

catches to predict larval density the following year, and obtained an r^2 of 61% which is quite encouraging (Fig. 6).

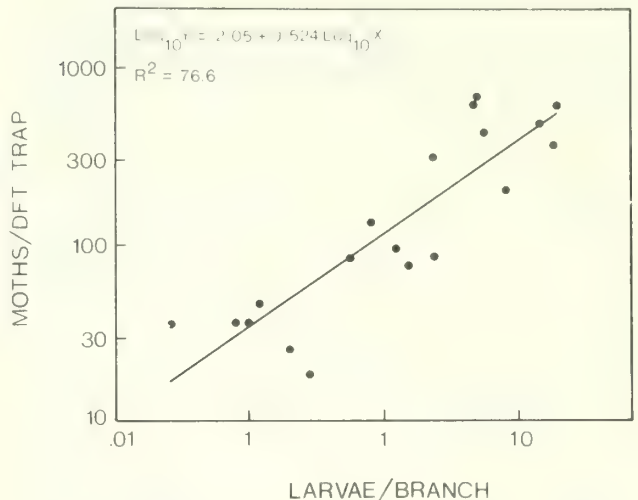


Fig. 4. Relationship between catches in double-funnel traps and larval density (Ontario, 1982).

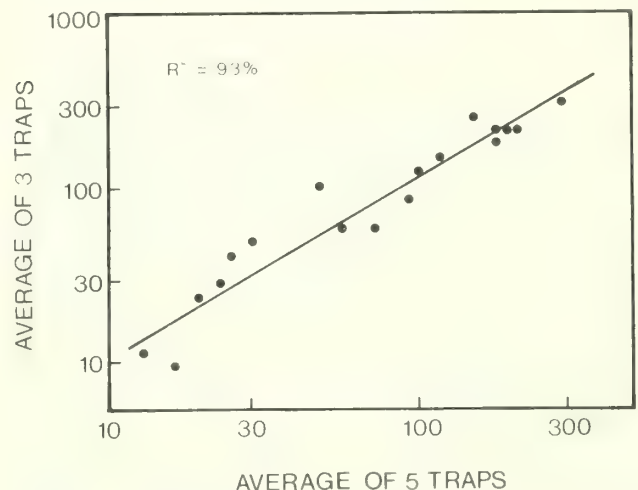


Fig. 5. Relationship between average catch per trap in clusters of 3 traps and clusters of 5 (Ontario, 1983).

e) New Trap Designs

In 1983 we carried out some comparative tests of other commercial trap designs. These were the International Pheromone Limited, Uni-trap (IPL), Baker Chemical 'Bag-a-Bug' and 2 Health-Chem products, the gypsy moth carton and gypsy moth canisters (Fig. 2). The last 2 were modified by enlarging the openings to make them conform to other designs.

These traps, along with the DFT and CFT were placed out in 2 areas, one of relatively low density (< 2 larvae/branch tip) and the other high

(ca. 10 larvae/branch tip). At the higher densities, all designs except the Health-Chem carton captured reasonable numbers (Table 1). However, at the lower densities the Bag-a-Bug and both Health-Chem designs gave very low catches, low enough to make it questionable if they would be of value for monitoring low density populations, although higher potency lures might increase catches sufficiently.

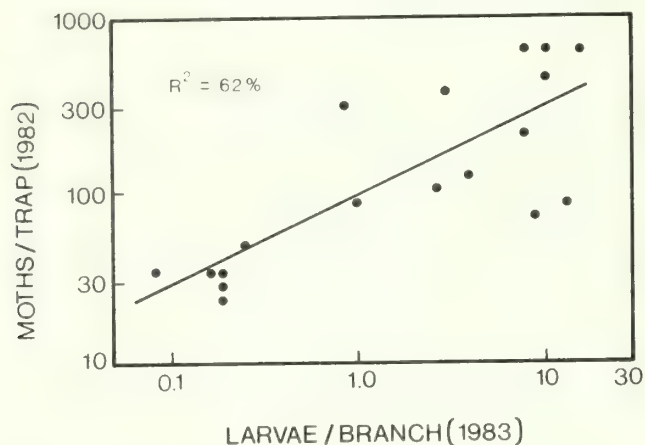


Fig. 6. Relationship between moth catches in 1982 and larval densities in 1983.

Table 1. Average catches in 6 different trap designs left out for 1 week during peak flight period in high and low population densities. The right-hand column provides an indication of the variation among catches in the low density population (each trap replicated 8 times).

	Population Density		Coefficient of Variance
	High	Low	
International Pheromones Ltd.	135	78	.24
Health-Chem "milk carton"	96	3	.44
Health-Chem plastic canister	21	7	.36
"Bag-a-Bug" canister	112	8	.36
Covered funnel	78	26	.40
Double funnel	139	39	.20

An important attribute of the catch is the variability among traps. This can be measured by the coefficients of variance which are shown for the 6 trap designs also in Table 1. The lowest values, indicating the least variation among traps was attained by the DFT and IPL traps.

Where then does this leave us? The traps have four attributes of concern--an adequate catch, convenience, cost, and durability. The six designs are rated for these 4 attributes in Table 2. Since adequacy of catch is of paramount importance the 2 Health-Chem designs and the 'Bag-a-Bug' are inadequate unless catches can be increased by higher potency lures. This is unfortunate, because their design is certainly the most convenient for assembly and storage. Of the remaining 3; the covered-funnel can be

excluded on the grounds that it allows moisture to enter, and that it is too inconvenient to assemble and store. The IPL trap is superior in all attributes except cost.

Table 2. Subjective evaluation of 4 attributes of pheromone traps. ++ = best, -- = worst.

	Catch	Convenience	Cost	Durability
Int. Phero. Ltd.	+	+	-	++
Health-Chem Carton	--	-	+	-
Health-Chem Canister	-	++	+	+
Bag-a-Bug	-	++	+	+
Covered funnel	+	--	+	+
Double funnel	+	-	-	++

Therefore, none of the designs can be considered the 'perfect solution'. My recommendation is that since the DFT has proven itself now for 2 years, it should be used as the operational trap in 1984, pending testing of other designs and modifications to existing designs. A change over from one design to another need present no serious problems. Provided each new design is in its turn, correlated with larval population densities, then a continuous integrated monitoring system can be maintained.

Already we have simpler more convenient and cheaper designs in mind. Also, modifications of the Health-Chem canister and Bag-a-Bug will be tried to determine if different configurations of entrances, and different colors would improve their catches in low density populations.

Trap Layout

The 1983 results showed that a cluster of traps, 40 m apart in a triangle, gave the same results as 5, 40 m apart in a star-shaped layout. Therefore it can be argued that 3 traps are sufficient. However, there is always the danger that 1 or 2 traps may be destroyed or lost. Therefore, we recommend the 5-trap layout, with the reassurance that if 1 or 2 traps are lost the remaining catches are still meaningful.

Distribution of Plots

The question of how far apart the plot should be to obtain an adequate picture of population change is difficult to answer. Certainly the answer must depend upon topography and size of forest stands. In homogeneous stand types few plots may be needed. In more broken country plots will need to be closer.

For seven years ICP traps were placed out annually in 30 locations in northwestern Ontario. The plots were located at interval along a triangular route approximately 400 km long encompassing an area of about 6500 km². Catches throughout the entire area showed a ver-

ood correspondence (Fig. 7), implying that one plot could have been used to represent the entire 500 km². In areas such as northwestern Ontario where climate and forest type are relatively homogeneous, 1 plot every few thousand km² may be adequate. But, in other areas plots should be located by stratifying the forest by stand type and climate.

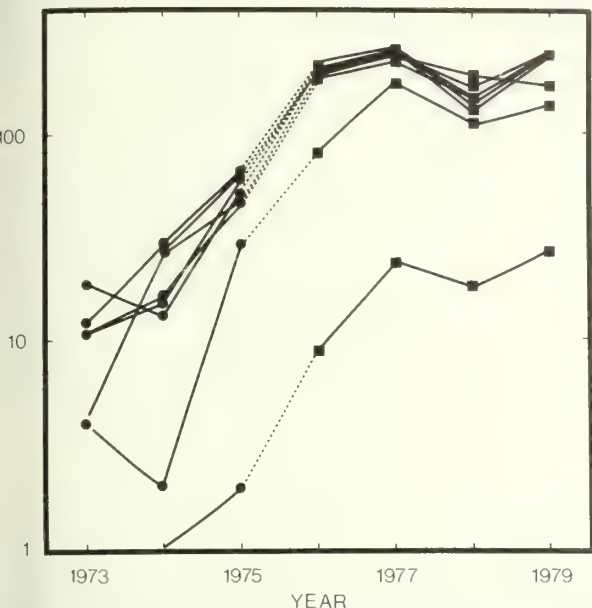


Fig. 7. Trends in moth catches (sum of 5 traps) in 8 plots in an area of 6000 km² in northwestern Ontario, 1973-1979. Solid circles "Sector 1" traps, squares Pherocon ICP traps. (Note similarity of trends even in lowest line which is for traps placed in centre of 6000 ha area burned in 1968.)

Lures

The second component of the trapping system which influences trap catches and their comparability from year-to-year is the lure.

The attributes of a good lure are:

- i) stability of the pheromone,
- ii) a release rate of 10-20 ng/hr,
- iii) a constant release rate for 6 weeks,
- iv) a comparable release rate from year-to-year.

The major components of the spruce budworm pheromone are unsaturated aldehydes. Such compounds are notoriously unstable. Fortunately, the fact that they are in the trap provides considerable protection from the elements, but the lure formulation must ensure protection from chemical and photo-degradation.

The release rate of 10-20 ng/ha is purely arbitrary. Female moths release the pheromone at approximately this rate, therefore, it is appropriate on biological grounds. Furthermore, this rate has been used for many years and has produced a good range of catches over a wide

spectrum of population densities. Fortunately, there appears to be a fairly wide tolerance to male response, and rates can vary $\pm 100\%$ without affecting capture rate significantly.

Release rates must be as constant as possible so that the capture rate is constant. A 6-week figure has been chosen since this allows time for the traps to be placed out before the moth flight, and collected up after.

Finally, to ensure that catches are comparable from year-to-year release rates must be constant from year-to-year, which implies that each batch of lures must be identical.

We have assayed 4 formulations of lure over the past few years: Hercon plastic laminated flakes; Albany International (Conrel) hollow microfibres; Bend plastic capsules, and polyvinyl chloride (PVC) pellets. The first 3 of these are commercial products, the last is a formulation made in our own laboratory which we have been using since 1973.

In 1982 and 1983, samples of each formulation were 'pre-aged' by placing them in a fumehood for various lengths of time. Lures of different 'age' were then placed out simultaneously to compare their rates of capture.

a) 1982 Results

The PVC pellets had a release rate estimated by New Brunswick Research and Productivity Council (RPC) at 10 ng/hr after 10 days, the Conrel fibres and Hercon flakes were designed by their manufacturers to have release rates between 10 and 20 ng/hr. The Bend capsules which were added to the experiment at the last moment had a far higher release rate, close to 2 μ g/hr. Lures were 'aged' from 1-6 weeks and results are shown in Figure 8. As anticipated from the release rates, catches with the Bend formulation far exceeded the others. Catches with the Hercon flakes were far lower than with either the Conrel or PVC although release rates were supposed to be similar. The Bend, Hercon and Conrel showed little variation in rate of catch with age (a desirable feature), but the PVC lures did.

b) 1983 Results

Catches with all 4 formulations were more comparable in 1983 than in 1982 (Fig. 9), indicating that release rates were closer, though by no means equal. The Bend was considerably less potent than in 1982, while the PVC and Hercon, relative to the Conrel were lower. As in 1982, the PVC lures showed a decrease in catches with age, the Conrel fibres were rather variable, while the Hercon flakes showed higher catches during the first week of age, all undesirable features. Only the Bend showed a relatively constant release rate, and so it must be considered the best of the 4 types of lure.

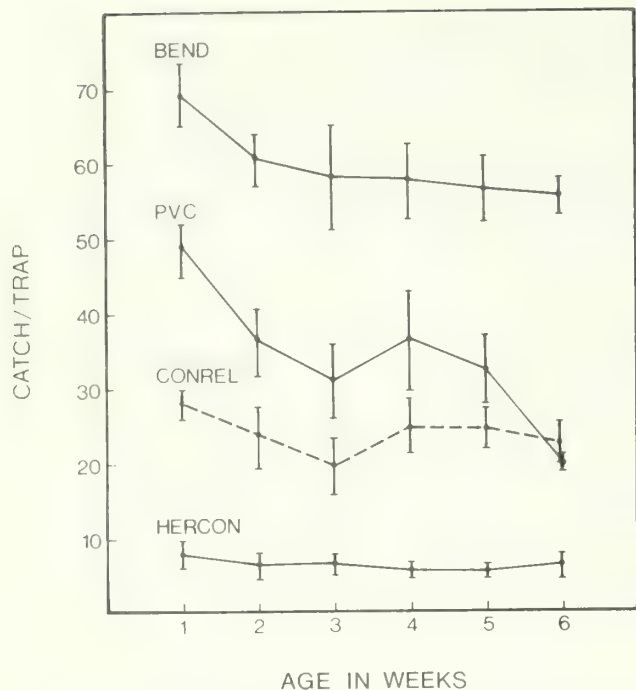


Fig. 8. Comparative catches in Pherocon ICP traps baited with 4 types of lure aged for different lengths of time (all deployed at same time) (Ontario, 1982).

Recommendations

Results up to this point in time (September 1983) demonstrate that non-sticky, non-saturating traps baited with synthetic pheromone of the spruce budworm are capable of monitoring fluctuations in low density spruce budworm populations, therefore of providing early warning of impending outbreaks. It is also apparent that they can be used to predict larval population densities, from one year to the next with reasonable accuracy, and may be suitable for replacing egg sampling.

However, it is important to remember that such a monitoring system must be standardised throughout the areas where the spruce budworm is a problem, and second, that to provide information for predicting year-to-year changes, the trap and lure must not be changed from year to year. Therefore, it is crucial to be sure that the operational system will stand the test of time. The current 'best' trap is not suitable for mass production, while the 'best' lure has not been adequately evaluated yet to be sure of its performance.

Therefore, it is recommended that there be a further year of testing, in which the following tests are carried out:

- Modified commercial traps are evaluated, using the DFT as a standard.
- Bend lures are tested over a wide range of population densities.

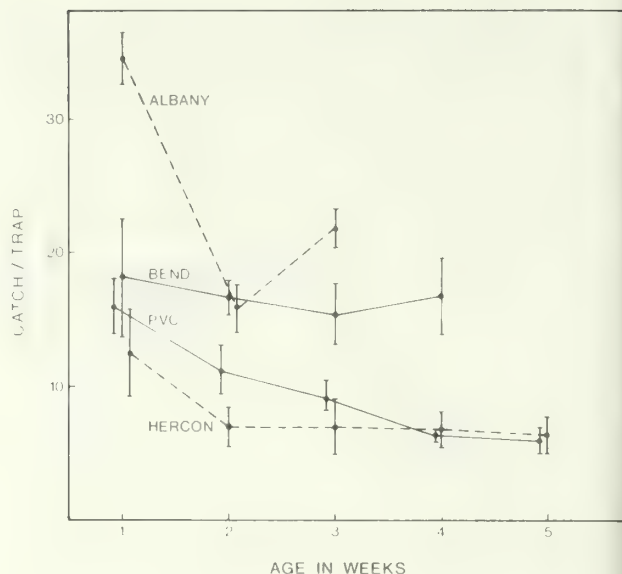


Fig. 9. As for Figure 8, but 1983 data.

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PHEROMONE-BAITED TRAPS

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Pheromone-baited traps are a promising new tool for monitoring spruce budworm populations. Further field trials of improved traps and lures and acquisition of time series data are necessary to improve methods and interpretation of trap catch. Preliminary results from recent field tests suggest that pheromone traps can be used to detect and delineate large-scale moth dispersal, predict population trend and predict population density or damage.

At present, it is not possible to unequivocally define specifications of a pheromone-oriented monitoring system for spruce budworm. Further refinements in trap design, lure characteristics and interpretation of trap catch data require additional field testing. Preliminary results from extensive field trials in Canada and the United States during the past three years, however, indicate that a monitoring system can be implemented in the near future.

We hope that this assessment and those preceding, will stimulate panel discussion on techniques and tools for monitoring spruce budworm. Those of us who have been involved with the field trials recognize the importance of dialogue between researchers and practitioners in order to maximize efficiency and ensure acceptance and implementation of a pheromone-oriented monitoring system.

Results of the 1983 CANUSA-East field trials will permit an analysis of the relationship of trap catches to a number of forest and budworm-related variables. These data represent 110 forest stands that occur in five states and four provinces. Cooperative field trials during the previous two years were beleaguered with logistical problems or inadequate traps and lures. Improvements were made during 1983, but additional work is necessary to assure that lures consistently provide suitable pheromone release rates and that trap catch will reliably reflect desired budworm variables.

Need for Time Series Data

A major concern that emerged from the 1981-1983 trials was the influence that local variations in budworm density, weather and stand conditions had on trapping results. Though it would

be nice to develop a single model to predict spruce budworm population trend or density in widely separated geographical locations, this may be an unreasonable goal. Preliminary data from the CANUSA trials and work with spruce budworm in Michigan (Ramawamy et al. 1983) and Ontario (Sanders 1983) indicate that a family of regional models, as opposed to a single model, may be necessary to provide reasonable confidence limits for predictions. Long term intra-regional (state or province) trapping surveys that follow a standard protocol and utilize a system of permanent plots are necessary to develop and test this hypothesis.

We believe that time series information from pheromone-baited traps will be at least as revealing as long term light trap data (Simmons 1980), without the cost or time consuming logistical problems characteristic of the latter. Also, the relatively low cost of a pheromone trapping system and its applicability at low budworm densities are advantages over the standard egg mass or overwintering larval (L2) surveys.

Assuming that average trap catch will provide a consistently reliable measure of budworm populations or expected damage, cost becomes a decisive factor when comparing the advantages of a pheromone system to other types of surveys. A major portion of the cost of any survey is travel to and between plot locations. Placement and recovery of pheromone-baited traps requires less time and equipment than other sampling methods. This will allow forest managers or survey specialists to implement the system while doing other types of field work. In other words, the major expense of travel can be minimized by combining the travel needs of a survey that uses pheromone traps with other field activities.

Management of a Pheromone Monitoring System

Maximum effectiveness of a permanent, large-scale survey will be attained only if survey responsibilities are centralized. Future application of a standard protocol should be closely supervised and augmented by annual training/review sessions. Experiences during the past three years demonstrated the value of organized review sessions to obtain input from practitioners. These interactive critiques, followed by on-site inspections, are necessary to assure uniformity of trapping procedures. Because we expect the system to change with experience and technical improvements, continuation of some degree of control is especially important. Similarly, centralized data management, that includes analysis, collation of results and dissemination of summary information should enhance opportunities for all agencies to obtain maximum value from future monitoring efforts with pheromone-baited traps.

Survey Procedures

The appropriate number of plots (one three- or five-trap cluster = one plot) must be determined by the agencies responsible for forest management activities or pest surveys. Survey intensity

will be determined largely by the significance placed on spruce budworm defoliation (i.e., hazard potential, resource value) and funds available. A few trapping locations may adequately indicate population trends over large areas (Sanders 1981).

In order to continually verify or "calibrate" the system, especially when alterations are made in the survey tool (e.g., trap design, lure characteristics), it is important to establish a minimum of 20 intensive plots in stands where another budworm life stage is annually measured. We envision multiple sets of these intensive plots. The plots included in each set must be selected according to similarity of stand conditions, climate and other factors. Clustering of relatively homogeneous plots will help to minimize statistical variation and provide more reliable models. Combining plots into regional sets for analytical purposes can be accomplished by survey management with help from forest managers, irrespective of political boundaries. Additional satellite plots can be established whenever users wish to extend survey coverage. These satellite plots follow the regular trapping protocol, but collection of supplementary budworm or forest stand data will be minimized. In order to insure future interpretability of satellite plot trapping data, base line information on stand composition, defoliation history and current defoliation is essential. Most of this information should be available from existing forest management records. The more extensive the coverage (plots per unit area of forest), the better forest managers and survey specialists will be able to monitor budworm. The benefits derived from additional plots must be weighed against their costs.

Application of Trapping Results

Mean trap catch can be quite useful within a decision support system for spruce-fir management. Absence of data limits interpretation of the relationship of catches in traps to long term trends, but preliminary efforts at short term predictions are encouraging.

Pheromone-baited traps can detect large-scale moth dispersal that may precipitate many outbreaks. This would be especially useful in remote areas where people are unlikely to observe flight activity. Trap catch would serve as a "pest alert" that provides lead time for a concerned forest manager to make traditional measures of budworm abundance, such as an overwintering larval survey. In addition to documenting the presence or absence of unusual dispersal activity, a network of trap-clusters will help to delineate the geographic area that has been invaded. Knowledge of rapid invasion is especially critical in high value forests, such as plantations, previously thinned stands or deer yards, where prompt action may be required to protect investments or sensitive areas.

Intra- and inter-stand time series data from permanently established plots is an inexpensive way to document and map budworm population trend.

Comparison of trend between stands and years may also be used to identify areas that warrant additional evaluation or require immediate silvicultural attention. Similarly, pheromone-baited traps can be used to detect significant population shifts in stands that have historically served as epicenters. The major contribution of this application is that reliable time series information will allow forest managers to anticipate problems several years in advance of significant defoliation. This advance notice provides lead time necessary to alter cutting schedules and plan control activities.

The most sophisticated use of information obtained from pheromone-baited traps is to predict population intensity (i.e., number of larvae or egg-masses/unit of food supply) or expected damage. Initially, interpretation of trap catch data may be used to describe population classes or categories (e.g., expected density low, medium, or high), or to identify a threshold above which significant damage may occur. For some forest managers, this information may be an adequate basis for making management decisions. As this survey system is refined, we anticipate being able to place confidence limits on predictions and, ultimately, to use pheromone-baited traps in place of other, more costly survey methods.

Average trap catch may also be applied in other ways to facilitate short term decision making by forest managers of pest control specialists. For example, adult population monitoring could serve as an index of spray efficacy or a means of timing other survey activities.

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REST PEST MANAGEMENT EXPERIENCES WITH SPRUCE

BUDWORM PHEROMONE TRAPPING

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In 1982, the USDA Forest Service began a special project to correlate trap catches with other predictions of budworm population levels and defoliation in outbreak areas. The 1982 trap catches were much lower than expected because the lure/trap combination did not work well and/or spraying reduced populations drastically. The 1983 trap catch did correlate with defoliation patterns in sprayed areas, and indicated that a mass flight occurred in western Maine. FPM impressions about pheromone trapping are discussed.

Our involvement with spruce budworm pheromone trapping began in 1982 when the Durham Field Office, Forest Pest Management, received special project funding. Also, both the Passamaquoddy and Penobscot Indians were conducting suppression projects in 1982. This activity gave us a location to work in.

Our project focused on demonstrating pheromone trapping in high population areas. Our objective was to correlate trap catches with egg mass, overwintering larval, large larval and defoliation estimates. We provided Doug Allen with data to use in the CANUSA pheromone project analysis. But our project differed from the CANUSA project in two respects. First, we were looking to work in high population areas. Second, we had aerial Bt applications in many of our clusters.

In each five trap cluster we used covered funnel traps and Hercon laminated lures in both years. Five clusters are located in northern Washington County on Passamaquoddy land. This area consists of spruce and hemlock with about 7% balsam fir. The balsam fir has completely gone by with only live balsam fir regeneration. Tree condition for spruce and hemlock is fair to poor with no kill common in hemlock.

Let's look at the 1982 and 1983 data. In 1982, populations averaged 13 large larvae/18" branch. Although this survey was timed for pre-spray counts, it coincided with third and fourth instar larvae. These clusters were sprayed with Bt and our moth catch averaged 23 moths/trap. In 1983, populations averaged 8 large larvae/18" branch. The clusters were sprayed again with Bt, and moth catch averaged 20 moths/trap.

I considered the moth catch very low in both years. In fact, the biggest concern I had before the project began was trap saturation. Why hadn't we caught more moths? I thought of two possible explanations. First, our lure/trap combination

does not efficiently capture moths that visit traps. Second, our spray projects were so successful that only a fraction of male moths were available to trap.

After our first trapping season, I called Doug Allen and told him about the poor catch. He thought the lures may not have worked well in 1982, but he felt that a correlation with low moth catch was still possible and maybe a blessing in disguise.

The 1983 trap catches were correlated with spray efficacy observations. In the northern spray block, foliage protection seemed poor (aerial observations) and traps averaged 30-35 moths/trap. In the southern spray block where foliage protection was good, traps averaged about 7-8 moths/trap. These results indicate that trap catches and foliage protection (or defoliation?) are correlated. This relationship deserves more attention, but these traps did have water in them. So, I wonder if these results are reproducible.

Fifteen clusters are located in western Maine on Penobscot land near Alder Stream. This more mountainous area consists of spruce and fir with much less hemlock and a large hardwood component. Budworm defoliated spruce and fir several years ago, but current tree condition is fair to good.

In 1982, populations averaged 3 large larvae/18" branch indicating a lower population than in Washington County. Nine clusters were sprayed with Bt in 1982. Traps within sprayed areas caught 3 moths/trap compared to 10 moths/trap in unsprayed areas. This difference indicates that spraying does affect trap catches.

In 1983, populations averaged only 0.7 large larvae/18" branch and this area was not sprayed. Trap catch increased sharply to 49 moths/trap - the largest average catch for both years. I thought of three possible explanations why the catch increased so sharply. First, these clusters were not sprayed in 1983. 1982 trap catch in this area does indicate that spraying affects trap catch. However, the very low spring larval population level suggests a mass flight occurred. A third possibility is that the lures performed more consistently than in 1982. Lures did work more consistently in 1983 because trap catch variation between traps in the same cluster was noticeably decreased.

Let me summarize my impressions of budworm pheromone trapping after two years experience:

1. Are low trap catches in high population areas a problem? Is our lure/trap combination effective?
2. 1982 gave a very poor correlation between trap catch and egg mass, overwintering larval and defoliation counts in 1982.
3. The ideal trap will prevent water from entering traps. Water retention can be a major problem.

4. Pheromone trapping is easy to execute compared to egg mass and overwintering larval surveys.

5. Not only lures, but insecticide strips, need to be carefully standardized.

6. Leaving trap hangars in the woods after trapping is completed is a safety hazard. I cut my ear on one.

Although we have not reached our goal of an operational pheromone monitoring system, we have made great progress. Don't throw away your pole pruners yet, as pheromone monitoring for budworm is on the way, and, it will be a valuable addition to our surveying and monitoring tools.

EXPERIENCES AND PROBLEMS

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Of the four different types of traps tested during the past three years, the covered funnel trap (CFT) was the most efficient at catching moths but some problems with water intake and retention remain despite annual modifications. Of the two gypsy moth traps tested in 1983, the canister trap produced the best results.

Introduction

Ideally the field testing of a pheromone trap as a survey tool should begin with a single trouble-free trap and lure combination that could be evaluated for several consecutive years. Unfortunately, problems with trap design and lure reliability have meant that we have had to work with four different traps and three different lures during the three years that Vermont has participated in the spruce budworm pheromone project. The one trap that was used each of the three years was modified in each successive year. These factors make it difficult to evaluate the results from one year to another. Specific observations and problems will be discussed by type of trap.

The Perocon LCP Trap

These "sticky" traps were tested with the VC pellet lure during 1981 and 1982. They are light and easy to use but most ended up with moth counts at or near the saturation point for the trap. A lure with a slower release rate might work well with these traps but with the lures tested, traps even in very lightly infested stands became saturated so that moth counts did not vary much between stands.

The Covered Funnel Trap (CFT)

The covered funnel trap (CFT) was the primary trap used in the project. It was used with the VC pellet lures in 1980 and with both the Hercon and Albany International lures in 1981 and 82. This is a non-saturating trap that has been the most efficient trap at catching spruce budworm moths. It has the advantage of being easily constructed out of materials that can be purchased locally but the disadvantage of being time-consuming to assemble and bulky to deploy and retrieve.

Most of the problems encountered with this trap relate to water intake and retention. The moths congregate in the bottom of the funnel and any water retention leads to partial decomposition of moths and attracts undesirable insects such as carrion beetles. Holes drilled through the bottom of the funnel just above the cork did not allow sufficient water drainage during the initial 1981 trials once moths were caught and began to congregate at the bottom of the funnel.

In 1982 corks were replaced by a wire screen plug placed inside the bottom of the funnel. This provided better drainage but it appeared that the air outlet may have reduced the effectiveness of the Vapona strip. This, along with release-rate problems with both commercial lures used, may have been responsible for erratic moth catch numbers within plots in 1982.

In 1983, the plastic cover plate was replaced by one of larger diameter to provide more overhang to shed water. The cork of 1981 was again used, with the addition of the wire screen plug above the drain holes. In making these modifications, we had to drill our own holes through the funnels and above the corks of traps first used in 1982. When traps were collected, it was discovered that if these holes were not flush or just below the top of the cork, water retention remained a problem. And in some plots with large moth counts (i.e. 100+), even correctly modified traps continued to have some moth decomposition problems because large numbers of moths congregated in the bottom of the wire plug and impeded water drainage.

The Gypsy Moth Canister Trap

The gypsy moth canister trap was compared to the CFT trap and the gypsy moth milk carton trap in 5 stands in Vermont in 1983 - four lightly infested stands and one that had become moderate. The trap is light, easy to use, and retains moths in a dry condition. It has the added advantage in that one is able to see if it is catching moths by looking up through the translucent bottom or down through the transparent top. It caught moths as early in the flight season as did the CFT trap. Height of lure suspension varied slightly from one trap to another because everyone bent their own lure-holding wires, but this did not noticeably affect the results. Generally, moth counts were much lower than with the CFT traps except for the moderately infested stand where the canister traps caught more moths. This trap caught more than four times as many moths in the moderately infested stand than in any other stand compared to about a two-fold difference with the CFT and gypsy moth milk carton traps. If this relationship holds true for other locations, this could be an advantage of this particular trap.

The Gypsy Moth Milk Carton Trap

The gypsy moth milk carton trap was tested in 1982 in the same stands where the gypsy moth canister traps were placed. It is the lightest

and simplest trap yet tested and also retains moths in a dry condition. It generally caught fewer moths than the canister trap and was not as efficient at catching moths early in the flight season as the canister trap. Even though these traps are made of wax-coated cardboard, they do absorb moisture over time. A couple of them were found hanging by only one wire at the end of the season because the sides became spongy and bent inward, slipping loose from the holding wire on one side. Bending the ends of the wires upward slightly would probably alleviate this problem.

General Observations and Discussion

Both commercial lures worked well in 1983 without the erratic within-cluster results from one trap to another that occurred in 1982. The Albany International lure consistently caught more moths in 1983 than the Hercon lure except when the two were compared in a moderately infested stand. The Hercon lure resulted in a noticeable difference in trap catch between the moderate and light stands that was not apparent with the Albany International lure. If this difference is significant and remains consistent in other locations and other years, it could be an advantage of the Hercon lure.

Northern and central Vermont received a mass flight of spruce budworm moths in July, 1983. It is not known to what degree this influenced moth trap results but it could make it difficult to correlate trap results backwards with data such as numbers of third and fourth instar larvae.

Any trap is subject to windfall damage and animal attacks. In 1983, one CFT trap was downed by a windblown tree early in the season and two gypsy moth milk carton traps were attacked by bears - one of these was completely demolished, and the funnel end of one CFT trap was chewed off by a squirrel. In 1981, one Pherocon trap caught a bird which reduced the numbers of moths that could be collected in that trap. A cluster of traps should be maintained for future monitoring so that data can be obtained even if 1 or 2 traps in a stand is lost. Whether the number of traps per cluster can be reduced depends upon the variability of the trap-catch data, but it is almost as easy and fast to use a five-trap cluster as it would be to use a smaller cluster.

Of the traps used in Vermont, the gypsy moth canister trap tested in 1983 was preferred by field personnel. It is light, easy to use, keeps the moths dry, and appears durable enough to last for several seasons. More testing of this trap with both commercial lures is recommended. The method of lure placement with this trap should be standardized, possibly by providing all users with pre-bent wires that would ensure that all lures are suspended at the height of the trap openings. It might be desirable to modify the lure suspension system so that it resembles that used in the CFT traps. But for consistency of results, it is suggested that any modifications be used in conjunction with a five-trap cluster and Hercon lures as used in 1983.

FOREST PEST MANAGEMENT CONCEPTS OF

GOOD SPRUCE BUDWORM PHEROMONE TRAP

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Many agencies and organizations in both State and Federal governments have experienced recent budget and personnel cuts. Consequently, many of us have had to restrict or limit our budworm monitoring activities. The pheromone trap has the potential of replacing more labor intensive spruce budworm surveys. More important, however, the pheromone trap is an additional tool to supplement existing survey techniques.

The characteristics of a good trap are that it should be weather proof, lightweight, portable, easy to construct, commercially available, and consistent in trapping performance. Forest Managers want a trap that is species specific to spruce budworm, a trap that acts as an attractant and not a confusant. They prefer a simple protocol or a simple set of instructions which covers systematic trap placement and allows for uniformity in data collection and compilation. Instructions should be presented in such a manner that data can be compared from province to province or state to state.

The sample design should be one that will allow trap placement in a minimum number of points or sites to get a representative readout on moth activity and potential defoliation for the coming year. Later, after eggs have been laid, more intensive larval sampling points can be set out for fine-tuning population levels. These two augmentative survey tools can then serve as basic data when evaluating the need for intervention or silvicultural management.

Pheromone traps will be useful in establishing baseline data during light infestations. Data collected from previous years will indicate whether or not a population is building.

Traps will also serve to identify pockets of heavy infestation for additional surveys and to provide a more concise analysis. As the population reaches epidemic proportions, other survey techniques will come into play. Their most efficient use will be in determining light or building populations.

Now that EPA has exempted pheromone attractants from FIFRA requirements (August 24, Federal Register), the door has been opened for much quicker implementation of new, more efficient trapping systems. This new ruling covers not only pheromones, but also synthetic compounds substantially similar to those actually produced by an arthropod.



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A pheromone monitoring system of spruce budworm moth activity may be useful to identify areas where more costly and labor intensive monitoring is justified. The system needs to be simple, non-labor intensive, and provide a volumetric classification. More research is needed to predict future outbreaks.

Early detection of changes in population levels of damaging insects is an essential element of forest management. As land managers, we have utilized the light traps to monitor moth activity and egg mass of L-II surveys to predict the next year's feeding, or population levels. Each of these three activities have unique points; both good and bad. Because other speakers are addressing the alternative activities to pheromone use at this workshop, I will skip lightly over them. However, I will attempt to briefly classify how I perceive these to be useful in our Company's program.

1. Light Traps. Incur a moderate monitoring cost, but require specific artificial energy sources to provide illumination. This activity is generally limited to low intensity sampling when used in wildlands or remote areas. Trap catches can indicate the possible severity of next year's insect activity and possibly identify a future change from endemic to epidemic populations.
2. Egg Mass and L-II Surveys. Require a highly labor intensive sampling and processing activity, with resultant high cost per sample unit. These provide valuable predictive levels for the severity of expected defoliation and insect activity. During epidemics or periods of known high infestations, the cost of the sampling is justifiable. In areas of endemic levels, it is very difficult to justify the high costs for monitoring individual stands.

What is needed is a moth activity monitoring program that is not labor intensive, does not require outside energy source, and does not require expensive processing or analysis. Use of such a system would be twofold:

1. To identify sampled stands that experience a level of moth activity that justifies more costly intensive

sampling or some other management activity.

2. To identify changes in historic levels of moth activity that would provide an early warning of a future outbreak. This early warning would allow managers to adjust forest management plans accordingly.

It has been assumed by many that pheromone traps may provide such a monitoring tool and research has been conducted as part of the CANUSA program.

My experience using pheromone traps is minimal and limited to participation as a cooperator in the CANUSA project led by Doctor Douglas Allen, S.U.N.Y. CESF, Syracuse. Indications are that pheromones will be useful in monitoring the high value or sensitive areas, but not necessarily the total forest. I believe that the traps will identify those specific locations where additional sampling is necessary and will result in a less costly monitor system overall than is currently in place.

The traps are easy to handle and distribute, and could be established and picked up (with the catch) by foresters, technicians, road crews, or temporary labor when they are working in or passing through the area. The catch should be in some sort of holding unit that allows classification on a volumetric basis. Absolute numbers I do not believe are meaningful or necessary if we are to use this method to simply identify areas where moth activity is substantial enough to conduct more intensive surveys. Furthermore, there is potential for pheromone trap catches to be used in identifying changes in trend and predict timing of future outbreaks which possibly may require a more specific count, but additional research is needed for this objective. I doubt that field personnel will extensively utilize pheromone traps for general surveys if the catches need to be hand counted.

The experimental traps have been easy to use and I expect that commercial gypsy moth traps of similar size, construction, and material to those used in the 1983 CANUSA test should be acceptable. The traps should be available for purchase through outside suppliers and be durable enough for several years use. The pheromone bait and the valpona strips should be readily available and easy to install.

One possible weak point in relying on pheromone trap catches to identify problem areas is the potential of fall or spring invasion of L-II larvae by wind drift. This weakness also exists for areas sampled in early fall by egg mass or L-II survey.

In summary, while my experiences with pheromone traps is minimal, I believe the outlook is good that a pheromone monitoring system of spruce budworm moth activity may be developed into a useful low cost tool to monitor high value

stands and identify where additional more costly monitoring is justified. The sampling method should not be labor intensive. Traps should be left in place four to five weeks during the moth activity period and then collected along with the catch by designated workers. The catch will be volumetrically classified by a management forester, technician, or entomologist at the office or lab following collection.

Finally, before pheromone traps can be used operationally in spruce budworm monitoring to identify potential outbreaks while in endemic situations, more research data and effort is necessary to signify the importance of trap catches.

Thank you.

Response to Program Discussion

1. In Maine, the Maine Forest Service conducts the general statewide monitoring system. Our use of pheromone traps would be to supplement the State's program. The selection of stands to be monitored by us would not necessarily be part of a State monitoring system but would be restricted to those high value or sensitive stands where prompt protection or other action is warranted; this would concur with the objective referred to by Doug Allen as a "pest alert system."

2. Implementation - We would expect to use this tool in low population areas of the current epidemic, but primarily we see this being most useful following the full collapse of the present epidemic, in sampling low populations prior to the next outbreak. We must remember that during the period following the collapse of this epidemic, foresters and those involved with daily field work may not have had field experience during high population levels of spruce budworm and most of their knowledge about the spruce budworm will be through the literature only. History has indicated that when populations are low and insects are not a problem, the overall concern for monitoring diminishes as well as the funds available to conduct monitoring. Thus, I believe a low cost pheromone monitoring system not requiring high labor costs or highly technical labor involvement will be more readily acceptable as an operational tool.

3. A comment was made that it may be necessary for two special field trips to place and remove the traps and that this cost may result in pheromone systems being more expensive to operate than the L-II or egg mass programs which require only one field trip. Our intentions are to possibly use pheromones where personnel are travelling in the area on other assignments and the establishment or collection of traps would incur only minimal costs and effort. However, if

we found it necessary to make special trips, we would consider the use of other alternatives, selecting the most efficient and cost-effective.

4. In response to the question of how useful a pheromone trapping system would be without having absolute counts, again I state that our primary use of this monitoring system would be as a pest alert where absolute numbers are not necessary but an index would be the output. The index could indicate areas of no concern, areas where additional surveys should be conducted before fall, or perhaps where levels of activity is such that some treatment activity should definitely be considered and supplemented with an L-III or L-IV verification prior to implementation of the treatment.

5. Dennis Suoto's presentation included the objective to evaluate spray treatments. Yes, I assume one could use this to supplement the post treatment surveys and determination of efficacy. We often find larvae present after the spray treatment and at times we find that these larvae do not complete their development to the adult stage. Thus, efficacy surveys of treatment areas might include measured mortality plus reduced moth activity as compared to unsprayed areas.

ASS SURVEYS

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When estimating egg mas density, two kinds of
rors usually occur: those from random chance and
ose from human sampling and counting errors.
andom chance errors cannot be avoided, but human-
used errors can be decreased by taking certain
ecautions. This paper offers guidelines to minimize
man-caused errors.

Egg mass surveys are commonly used to gain a fix
spruce budworm populations and expected damage.
rors, however, can creep into these surveys and
ssibly influence reliability. To begin with, egg mass
nsity estimates are highly variable, often deviating
om "true" populations densities by 100% or more.
ese deviations result from the small samples we take
mpared to all the branches that could be sampled in
forest. The resulting "random" estimating errors are
known to us and cannot be controlled by what we do.

Other errors occur from the way we sample and
unt. These usually occur when we

- a) sample one host species in stands containing multiple host species,
- b) sample too low or too high in the tree crown,
- c) use small branches as the sample unit,
- d) make rough estimates of surface area when calculating egg density,
- e) assume egg masses do not vary in size from one generation to the next.
- f) do not distinguish between new and old egg masses when examining foliage, and
- g) make counting errors when searching for egg masses,

the following, we discuss each source of potential
ror and provide guidelines for taking precautions to
nimize such error.

Tree Species in a Stand of Mixed Host Species

Surveys often concentrate on sampling balsam fir
en though white and red spruce may also comprise
ands. Our studies show that in white spruce/balsam
stands, egg densities are 2 to 4 times higher on
white spruce than on balsam fir. Restricting sampling
fir trees could result in underestimates. To counter
is error, include fir and spruce in rough proportion to
sal areas of each in a stand.

Branch Location

Branches selected from the upper third of the live
crown of a tree tend to overestimate populations, and
estimates tend to be highly variable. Branches selected
from the lower third of the live crown tend to
underestimate populations, and again estimates are
highly variable. Sample branches taken from the
middle third of the live crown tend to slightly
overestimate population densities, but the variability is
much less than the other areas of the crown. To
minimize error, sample from the middle third of the
live crown.

Branch Size

Egg mass sampling schemes have used 15-inch
branches, 18-inch branches and full-length branches.
Our studies show that when using full-length branches
estimates vary the least compared to all other branch
lengths.

Surface Area Measures

Egg mass surveys sometimes report number of egg
masses per unit surface area (10 ft^2 or m^2 or 1000 cm^2). Ways to estimate surface areas include (a)
measuring the length of the branch and multiplying by
the width at the midpoint, and (b) cutting up the branch
into small segments and placing on a grid. We have
found the grid method is the most consistent measure
of surface area.

Old and New Egg Masses

A small percentage of egg masses are retained on
foliage for more than one year. Consequently, densities
may be overestimated because both old and new are
counted. Here are some guidelines that may help
distinguish between old and new egg masses.

- (a) If egg masses are found on current year's
foliage, they are definitely new egg masses.
- (b) Color, shape, and condition of egg masses can
be of some help; the tendency is as follows:
New: bright white, bulgy, intact
Old: brownish-gray, flat, deteriorated

Size of Egg Masses

Egg mass densities are usually reported as
"number of egg masses per square ft of foliage." This
implies that the number of eggs in a mass is the same
from mass to mass and year to year. Our studies have
illustrated that the average number of eggs per egg
mass varies from year to year and locality to locality.
We suggest taking a sample of egg masses and
determining average egg mass size each year to correct
for these differences.

Egg Mass Searching

While all counters will underestimate egg mass
numbers, the extent to which individuals overlook egg
masses varies widely. In addition, counting accuracy

for a given individual may vary with time, egg mass density (low, medium, or high), or tree species being examined.

We have developed a simple method for adjusting egg mass density estimates for accurate counts and therefore more accurate conclusions based on the resulting data (Fowler and Simmons 1980). Four steps are involved in applying a bias adjustment to counts obtained by examining tree foliage for egg masses:

- (a) determine the range of egg mass densities expected in the survey,
- (b) check the accuracy of each individual involved in counting,
- (c) calculate the average counter accuracies for each examiner, and
- (d) use the accuracy estimates to adjust counts for each examiner.

The accuracy of each counter on the crew can be determined by carefully checking individual branch samples that already have been counted by a member of the crew. The supervisor or the most experienced counters should conduct the checking process. Fifty or more branches per counter for each density class should be checked (Fowler and Simmons 1980). Checking should be done periodically and without the counter knowing when a branch is going to be checked.

Once the checker has re-examined the branches for egg masses, the average counter accuracy can be determined. Estimates of accuracy should be determined for each counter for each egg mass density level encountered during the survey. If time and resources permit, other factors can be considered when determining accuracy estimates for each counter.

Once accuracy estimates have been determined they can be used to develop more accurate (less biased)

estimates of egg mass density. Readers interested in the details of this bias adjustment technique should consult Simmons and Fowler (1982). For a more in depth understanding of the derivation of the technique see Fowler and Simmons (1980).

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UTOMATED EGG MASS COUNTER

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Reviews the design and development of an automated egg mass counter. The counter scans foliage samples, detects egg masses based on their characteristic fluorescence, and counts the egg masses electronically.

Egg masses of the jack pine budworm (*Choristoneura pinus pinus* Freeman), the spruce budworm (*C. fumiferana* (Clem.)), and the western spruce budworm (*C. occidentalis* Freeman) fluoresce when excited by longwave ultraviolet (UV) light. The excitation wavelength extends from 300 to 400 nm. Early tests demonstrated that both accuracy and efficiency of egg-mass examinations can be increased by inspection of foliage illuminated with UV light (Jennings 1968; Acciavatti and Jennings 1976).

A study was initiated at the University of Maine, Departments of Physics and Electrical Engineering, in collaboration with the Northeastern Forest Experiment Station and the Department of Entomology, to determine: 1) the fluorescence properties of spruce budworm egg masses; 2) the fluorescence properties of associated components on balsam fir foliage; and 3) the feasibility of using these properties to scan foliage, detect egg masses, and count the egg masses electronically.

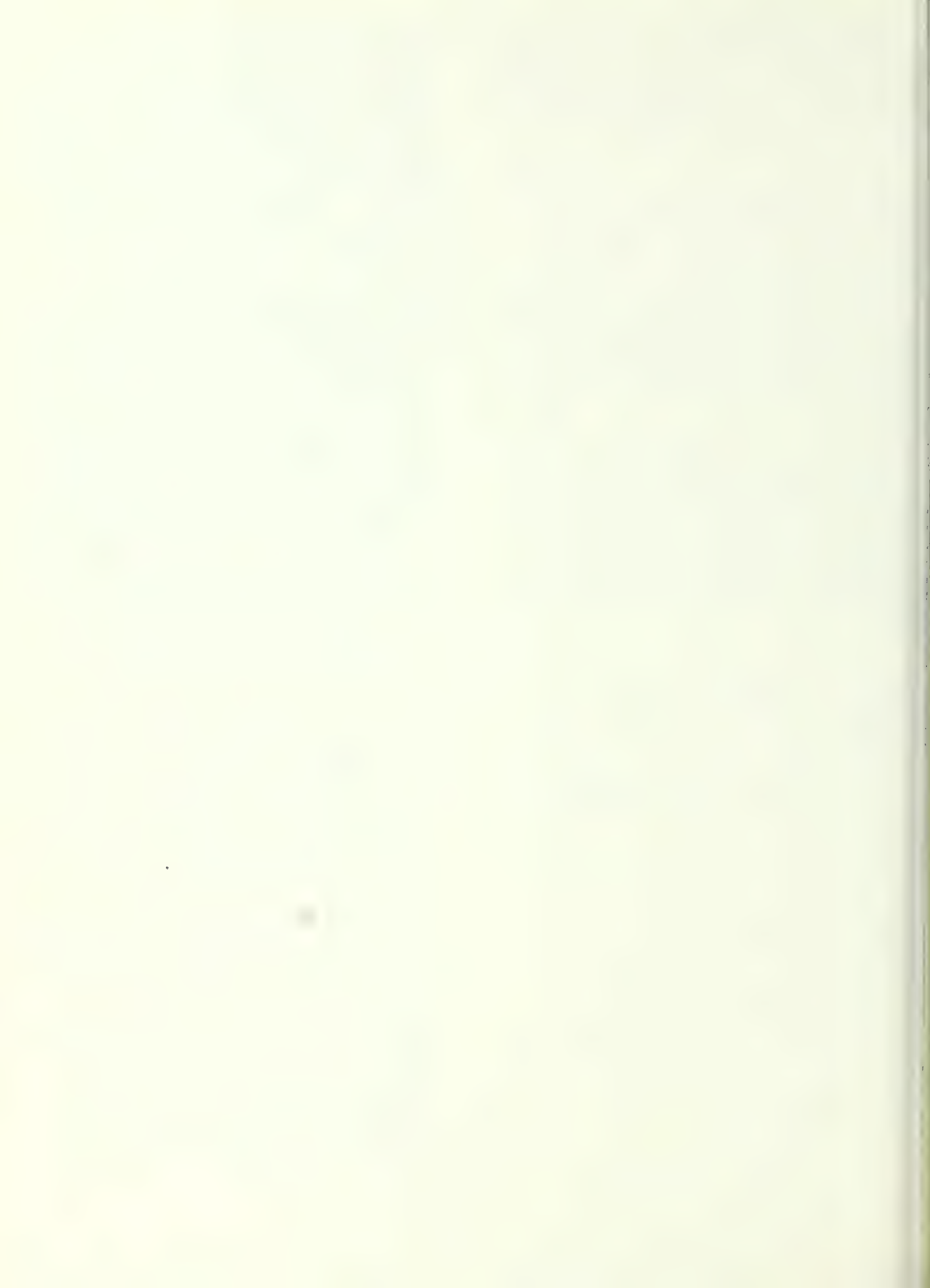
Spectral analyses indicated that egg masses of the spruce budworm have a characteristic violet and green fluorescence that is distinguishable from most other fluorescing components on balsam-fir foliage (Carniglia et al. 1977). Egg mass fluorescence is predominately violet light, but the ratio of green to violet fluorescence is also important. By measuring fluorescence levels together with ratios of green to violet fluorescence, egg masses of the spruce budworm can be distinguished from most other fluorescing objects on host tree foliage.

A Prototype I egg mass counter was designed and built at the University of Maine. Basic components of the counter include: an electro-optical scanner, beam splitter, photomultiplier tubes, and electronic signal discriminator. Preliminary tests of Prototype I vs. manual counts indicated that, when calibrated, manual counts can be predicted ($R^2 = 0.97$, $\alpha = 0.01$) from electronic counts (Turner et al. 1980). Electronic counting showed a highly significant reduction in processing time; electronic $\bar{X} = 8.6$ min./branch vs. manual $\bar{X} = 29.5$ min./branch, $n = 477$ branches.

A Prototype II egg mass counter is being designed and developed at the USDA, Forest Service, Missoula Equipment Development Center, Fort Missoula, MT. New design features include: a variable optical scanning system to detect egg mass fluorescence of both spruce budworm and western spruce budworm egg masses on 5 host tree species (balsam fir, spruce, Douglas-fir, white fir, and grand fir); a stepper motor-variable belt drive system; and a programmable computer (microprocessor) with terminal for operation and maintenance. The new Prototype II includes an "egg hunt" routine for scanning foliage until an egg mass is found, stopping, and then allowing the operator to look at what the counter "sees".

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Introduction

This paper is a discussion of work done in the winter of 1982-83 by the Maine Forest Service (MFS) to evaluate and improve the over-wintering larval sampling method (L-2 method). The MFS has used the caustic soda larval extraction method developed by Miller et al (1971) since the mid 70's as a supplement to the egg mass population prediction survey. This paper will also include a brief discussion of evaluations conducted from 1978 to 1983 designed to test the predictive power of the L-2 method.

The desire to evaluate and improve the over-wintering larval extraction method in Maine was motivated by two factors. First, egg mass sampling conducted in the late 70's proved to be erratic and resulted in several erroneous predictions. Egg assessments both overestimated and underestimated populations in those years. Second, the L-2 method seemed to present an excellent opportunity to reduce survey costs by reducing the time required for laboratory assessment. Even when relatively crude methods were employed in the late 70's, 2 or 3 laboratory workers using the L-2 method could evaluate as many samples per week as an 8 person egg mass laboratory. When spruce is included in the survey method, the L-2 method has an even greater laboratory advantage.

Much of the work summarized here is ongoing, it was used in the 1983 Maine population prediction survey. It has not been published, but no publications are expected. One publication will deal with the predictability of the L-2 method and the second with L-2 laboratory and field procedures.

Funding for this work has been provided by the Maine Forest Service and Maine forest landowners through the Maine budworm excise tax. Several useful suggestions on method development have been provided by the Eastern Spruce Budworm Council, Committee for the Standardization of Survey and Assessment Techniques.

Methods

To contrast the new techniques discussed, the method used by the MFS through the 70's will be described.

The original technique employed was that of Miller et al (1971) and involved collecting 4,

three foot fir branches from a collection site, cutting each branch into 3-4 inch sections, bagging the foliage from each branch separately and transporting it to the laboratory for processing.

The foliage from each branch was placed in a pail, approximately 1/3 cup of lye (NaOH) added, and the bucket filled with hot tap water from a garden hose. Water temperatures varied from 120° to 180°F. These buckets were set on the floor, manually stirred every 15-20 minutes, and the foliage allowed to soak for 4 to 6 hours.

Following soaking, the foliage and contents of each bucket were poured and washed through progressively smaller sieves and the remaining substrate collected on filter paper for larval counting. Larval counts were extrapolated to 100 square feet of foliage.

In the early years of the survey, few samples were processed annually. Admittedly, the original laboratory techniques and the laboratory facilities were quite primitive. As the size and importance of the survey grew, mainly due to problems with the egg survey, it became apparent that improvements both in extraction methods and in the laboratory facilities were necessary.

Changes were made in the L-2 method and facilities to accommodate the expanded scale and importance of the survey. First, a facility was designed and built specifically for the L-2 process. A 22' x 18' building was renovated for the laboratory. Significant changes from former facilities were:

1. A mechanical, 4 shelf, vented, shaker box designed to provide constant sample agitation and to maintain water temperatures longer
2. Installation of an unlimited hot water supply
3. Segregation of the "washing" and "counting" rooms
4. A metered and temperature regulated water supply
5. An efficient, self-contained washing table which makes all chemicals available at one location
6. Multiple filtering and counting stations with vacuum regulated through a vacuum pump

Changes in the field procedure involved a change from 4 fir branches per point to 3 fir and 3 spruce branches per point.

Several facets of the laboratory method were evaluated to determine the optimum NaOH concentration and water temperature. Soaking time, the agitation system, the rinsing system, and total larval extraction were also tested. Regimes tested are as follows:

% NaOH	H ₂ O Temp. °F.	Treatment
1.5	100, 120, 140	2 hrs.+2 hrs., 2.5@120°
2.5	100, 120, 140	2 hrs.+2 hrs., 2.5@120°
3.5	100, 120, 140	2 hrs.+2 hrs., 2.5@120°
3.5	120	1 rinse vs. 2 rinses
2.5	120	3-2 hr. soaks
2.5	120	2 hrs. shaken vs. 4 hrs. on floor

All tests were done with a standard 6.0 liters of water at carefully regulated temperature. Buckets were stirred manually every 30 minutes while still in the shaker box.

The predictability of the L-2 method was checked by correlating L-2 counts with L-3 spring counts. Evaluations were made using stepwise multiple regressions and covariant analysis. Data analyzed was gathered as part of the regular MFS survey and includes fir and spruce assessments.

Results and Discussions

Initial tests of the new laboratory facilities and equipment were encouraging with regard to sample output. A laboratory staff of 4 workers was able to process 100 branches daily compared to less than 30 branches per day from 4 egg mass workers. The laboratory can be easily expanded to a capacity of 120 to 180 branches per day by adding 2 more workers. Spruce is only slightly slower to process than fir compared to being more than twice as time consuming with the egg method. All equipment worked extremely well after many initial design changes. One lingering equipment problem is the shaker box. Due to extreme stress on the vibrating shafts, bearings, and drive belts, parts fail often. Spares are always kept and can be installed quickly. The vibrator may be redesigned.

Trials of extraction efficiency were surprising and discouraging. Extraction efficiency was relatively consistent, but only 35 to 40 percent of the over-wintering larvae were being recovered on the filter paper. It was initially thought that the poor efficiency was due to the short soaking time, the NaOH concentration, or water temperature.

Before extensive method testing was started, brief initial trials were conducted to identify major problems with the method. The first surprise encountered was that NaOH percentage and water temperature, while important, did not account for loss of the major portion of unrecovered larvae. Another trial showed that most larvae were lost because of inadequate rinsing of foliage after soaking. Losses here could be as high as 30 to 40%. An intensified rinse system was established and brought recovery percentage into the 60 to 75% range. The new rinse method

was used in all future tests.

Tests of NaOH percentage and water temperature were designed to determine optimums. Results of a statistical analysis of these tests are shown in Table 1.

Table 1. Statistical Analysis of Larval Extraction Variations.

Temp. °F.	% Concentration NaOH			
	1.5	2.5	3.5	
100	60.9 ^{1a2}	65.9 b	79.3 b	
120	70.6 b	84.4 c	83.5 c	
140	77.5 b	86.6 c	89.3 c	

1. Percentage of total larvae recovered from 2 soaking trials with the 1st soaking.
2. A common letter indicates no significant difference in larval recovery.

All NaOH concentrations and temperatures extracted 60% or more of total larvae recovered. Total larvae were estimated on the basis of 2 washes. Regimes of 2.5% NaOH at 120 and 140° F. extracted more than 83% of the larvae with the first soak. None of these 4 regimes gave statistically different results. As a result of this test, a standard regime of 2.5 percent NaOH in 120° F. water was adopted for the 1983 survey.

The question of what portion of the total larvae on a branch are extracted by 2 soakings was answered with a test involving 3 soakings. This test showed that the 3rd soaking yielded less than 2.5 percent of the total larvae recovered. This result shows that recovery percentages reported are probably accurate.

The rinsing process which had been established early in these tests was further evaluated to check its effectiveness. Results showed that a second rinse yields about 8% more larvae with a small increase in laboratory effort. As a result of this test a second rinse was added to the standard method.

A two hour soak in the shaker box was found to be more efficient and more consistent than a 4 to 6 hour soak with 15 minutes stirring.

The most important result of the 1982-83 L-2 trials in Maine was an understanding of the importance of each part of the method and its impact on accuracy. The current method as developed from these trials is as follows:

1. Use of the shaker box
2. Water at 120° F
3. NaOH at 2.5%
4. 2 Hour soak time

Hand stirring every $\frac{1}{2}$ hour

Use of an aggressive rinse system using 2 rinses

Tests of the predictability of the L-2 method have been underway since 1978, but these tests are done using the former low efficiency extraction techniques. These tests will be repeated in 1983-84 with the new extraction techniques.

Results of the predictability test conducted in 1981 showed that L-2 counts are highly correlated ($r^2 = .75$) to spring L-3 counts. Correlation to L-3 counts can be improved to $r^2 = .84$ if spruce counts and past defoliation values are considered in the form of a stepwise regression analysis. Past evaluation of egg count correlations to L-3 values have yielded much lower correlations ($r^2 = .65$). In general terms, the Maine L-2 method is an accurate predictor, about 50% more often than the Maine egg mass survey.

Tests have shown that L-2 samples taken in September and October correlate very well with March-April samples ($r^2 = .90$). This information allows the MFS to conduct the general L-2 survey in a time frame which allows landowners to make management decisions based on this data.

It is encouraging that the apparently good population prediction survey using L-2 costs less than the egg survey. Field costs are equal, but laboratory costs are about 30% less with the L-2 method. Potential for L-2 method improvements is also significant. A sequential counting system for the laboratory could be developed. The L-2 method has much potential for mechanized counting using technology similar to that used to count spray droplets. The present and future usefulness of the L-2 method will some day lead to its use as Maine's sole population prediction method.

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POPULATIONS

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Current techniques used for sampling spruce budworm populations are discussed in light of the intrinsic difficulties presented by low pest densities. Methods of recovering parasitoids are reviewed. The need for continued observation of natural control factors through endemic periods is stressed.

Sampling Sparse Budworm Populations for Parasitoids

The eastern spruce budworm parasitoid complex has been relatively well-studied in epidemic populations (Dowden et al. 1948, Wilkes et al. 1948, McGugan and Blais 1959, Blais 1960, Miller 1963). Like many other host-parasitoid communities, only limited data have been obtained at endemic or sparse population levels, largely because of the major effort associated with finding sufficient numbers of spruce budworm (Miller and Renault 1976). Sampling to obtain valid estimates of the degree of parasitism in moderate to heavy populations of spruce budworm presents a difficult problem (Lewis 1960). In endemic situations, establishing population size of the host alone is onerous (Miller and Macdonald 1961). Dowden and Carolin (1950) found that determining the number of spruce budworm in an area is probably the most difficult research problem associated with this insect, and that it is not possible to present the true value of mortality percentage figures unless data on density of spruce budworm populations are available.

Spruce budworm sampling procedures have been reviewed recently (Sanders 1980). Procedures are grouped according to the stage of the insect's life cycle being sampled: egg, second instar larva, large larva, pupa, or adult. While gross estimates of population density are possible with many sampling methods, it is difficult to define the relationship between low density and required sample size (Miller 1964).

Egg mass sampling, a procedure for assessing and predicting spruce budworm population trends, has traditionally been tedious and time consuming, and some egg masses are missed even by experienced workers (Morris 1951). When populations are low, egg masses are too scarce to be sampled efficiently (Trimble 1981). Even when populations are in

the outbreak stage, an adequate sample requires laborious searching of foliage to locate egg masses. To eliminate this problem, a conveyor-belt system for a prototype spruce budworm egg mass counter has been developed which detects and counts egg masses that fluoresce as they pass under a black light¹. Large amounts of foliage can be searched with increased accuracy and efficiency.

The "wash out" procedure for overwintering second instar larvae (Miller and McDougall 1968, Miller et al. 1971) is applicable to sparse populations, but, again, large amounts of foliage must be examined to attain precision. Both the automated egg mass counting procedure and the second instar larval counting method help to reduce inaccuracies due to human oversight. Predictive values derived from these new methods must change to reflect this greater precision. Factors like egg mass size variation resulting from different host tree species also need to be considered in the development of predictive tables and regression equations (Washburn and Brickell 1973).

Miller and Macdonald (1961) suggested that indirect sampling methods, such as the analyses of bird gizzard contents, might be useful in population work since birds are efficient samplers of large larvae. Although the inherent population limitation of birds prevents them from increasing enough to check outbreaks, they may be valuable when the budworm population is low (Graham and Orr 1940). The analysis of the gizzard contents of four species of warblers from the Green River Watershed in New Brunswick showed 0.5 larvae/gizzard in 1959 and 0.27 in 1960, or a population reduction of 46 percent (Miller and Macdonald 1961). Actual population counts showed a reduction of 70 percent (0.275 to 0.082 larvae/m² foliage). For more exact predictions at these low levels, some refinement of technique is necessary.

The effect of killing birds to ascertain low spruce budworm populations can be detrimental. This was verified by Dowden et al. (1953) who found a far greater reduction in budworm populations in check areas where birds were unmolested than in areas where their numbers were reduced by shooting.

Certain species of birds show limited numerical response to increasing spruce budworm densities although they do not contribute significantly to the regulation of the spruce budworm at high densities (Morris et al. 1958). Sanders (1970) suggested that the reduction in numbers of certain bird species known to respond numerically to spruce budworm increase can be predictive of the population trend of the spruce budworm.

¹/ Jennings, D.T., 1983, personal communication.

The use of pheromone traps for monitoring adults in low level spruce budworm populations is currently being evaluated (Allen and Abrahamson 1982). Field experiments are in progress in New England and the Lake States to gather trap-catch data for correlation with subsequent counts of egg masses, estimates of larval density, and defoliation. Researchers are also trying to determine the most effective placement and spacing of traps in such a monitoring system. The use of light trap data for assessing changes in endemic spruce budworm populations is being evaluated (Simmons 1980).

Some techniques useful in spruce budworm epidemics are not reliable when densities are low. For example, although reasonably accurate estimates of tree defoliation can be made by trained observers from aircraft when budworm populations are moderate to heavy (Waters et al. 1958), the absence of discernible defoliation is a weak guarantee that the spruce budworm is absent. Similarly, methods currently in use to evaluate and classify defoliation from the ground (Fettes 1950, Dorais and Hardy 1976) may not work as indicators of population levels when defoliation is negligible.

When removing foliage for subsequent counting and classification, the number of sampling units required, i.e., 45 cm branch tips, whole-branch sample, or other units, increases rapidly as population densities decrease (Sanders 1980). Life tables become more difficult to construct because low pest densities discourage attempts to procure fixes at more than one or two of the insect's developmental stages. Consequently, year-to-year changes in one developmental stage, rather than survival within each age-interval, are analyzed (Miller and Macdonald 1961).

The difficulty in collecting sufficient numbers of individuals is reflected in the rarity of concrete assessments of mortality factors in endemic population studies. Blais (1959) and Fye (1963, 1965) investigated endemic populations in the Gaspé Peninsula of Quebec and Ontario, respectively. Miller and Renault (1976) conducted parasitoid studies in endemic spruce budworm populations in New Brunswick.

Our investigations of the parasitoid complex associated with endemic populations in Vermont began in 1980. Spruce budworm population criteria for establishment of study plots were 1) that overwintering larval counts be $<3/m^2$ of foliage and 2) that the previous year's defoliation was $<30\%$. Degree days accumulated above a base temperature of $5.56^{\circ}C$ were used to predict the development of post-diapause budworm (Miller et al. 1971).

Spruce budworm larvae and pupae were collected from six plots at four periods of development. Collection periods (described

below) represented optimal times to assess the incidence of certain species of parasitoids (McGugan and Blais 1959, Leonard and Simmons 1974).

1. Predicted mean of third instar. The best estimate of population density may be provided by third instar population (Greenbank 1963). Because mortality due to parasitoids is considered almost nil at this stage (Morris and Miller 1954) and because of rearing difficulties associated with the tiny larvae, few have undertaken collection of this instar in parasitoid studies.
2. Predicted mean of fourth instar. The abundance of early larval parasitoids and an indication of the sequence of attack of the late larval parasitoids can be derived from fourth instar budworm.
3. Predicted mean of sixth instar. This timing should coincide with the maximum abundance of late larval parasitoids.
4. Predicted mean of pupation. Incidence of pupal parasitoids can be measured from this collection.

The speed at which spruce budworm develop necessitates a concerted sampling effort to ensure that all samples are taken within the desired degree-day range.

Branch samples were clipped with pole pruners from random positions in the midcrown of sample trees. As larvae mature, the probability of their dropping off branches when disturbed increases (Sanders 1980). Therefore, basket attachments or branch holders on pole pruners were used for sampling large larvae.

The number of branches sampled during any collection depends on the number of insects present and the objectives of the survey. It is extremely important to record the number of branches sampled to find the desired number of spruce budworm.

Methods of Determining Parasitism

Several methods have been employed for the measurement of spruce budworm parasitoid activity. These range from indirect methods, such as trapping of adult parasitoids (Nyrop and Simmons 1982) and sampling foliage for parasitoid cocoons (Simmons and Chen 1974), to direct recovery of parasitoids from spruce budworm hosts.

Recovery of parasitoids is accomplished in two ways. They can be obtained by dissecting field-collected host larvae and pupae, or they can be reared from collected eggs, larvae, and pupae in the laboratory.

Dissection techniques have been described by Kemp and Simmons (1976). For ease in handling, it is recommended that larvae be refrigerated at 7.2-10.0°C before dissection. Each larva is positioned beneath a compound microscope and held down with a probe. A cut is made posterior to the head capsule with the sharp edge of a syringe needle. The body contents are carefully forced out through the incision with the blunt side of the needle. Body contents are then examined for the presence of immature parasitoids.

Another dissection method is to make a longitudinal cut along the dorsal midline of the larva. The cuticle is then separated to expose the body contents, which are inspected for parasitoids. Immature parasitoids are preserved in 95 percent ethanol.

One of the advantages of dissecting for parasitoid recovery is that data can be obtained immediately and rearing procedures need not be undertaken. A major disadvantage is that identification of immature parasitoids is often very difficult, particularly for little-known species, and these are more likely to be found in endemic populations (Hanson 1982).

At the University of Vermont, we attempt to rear all budworm larvae and pupae collected for determination of parasitism. Several diet formulations have been tried, with highest rearing success achieved with pre-measured commercial preparations². The medium is prepared as directed and dispensed in 1 oz plastic creamer cups. "Drying" the medium for several hours after preparation by covering filled cups with sterilized blotter paper proves useful, although moisture may continue to collect in occasional cups.

Larvae are reared in environmental chambers or in air-conditioned rooms at 11°C and 60-75% relative humidity. Since isolation is desired for ease in matching host and parasitoid, spruce budworm are reared one per cup. Cups are examined daily and emerged parasitoids and moths removed. Because head capsule size of spruce budworm larvae is an acceptable determinant of instar (McGugan 1954), head capsules of all parasitized larvae can be measured with an ocular micrometer to determine the instar when each was collected and to evaluate the accuracy of the degree-day parameter used to anticipate proper sampling dates. These measurements also allow parasitoid incidence to be associated with the stage of the host both at the time of collection and at the time of emergence.

One of the major disadvantages of rearing spruce budworm for determination of parasitism

is death of the budworms due to unknown causes. Causes of spruce budworm mortality during laboratory rearing are difficult to assess (Miller 1959). Some mortality may result from nonacceptance of the diet by larvae. Handling of larvae, particularly during early instars, increases mortality (Robertson 1979).

Those individuals that die of unknown causes may or may not be used to calculate total percent parasitism. It is hypothesized that an equal proportion of these individuals are parasitized (McGugan and Blais 1959), so those budworms that die of unknown causes are sometimes not used to calculate total percent parasitism.

Radiographic techniques have been used to identify healthy, parasitized, and diseased larvae and pupae of various species (Odell et al. 1974). In this case, freezing and thawing the budworms disrupted the tissues to the extent that radiographs showed nondescript debris or partially liquified body contents. Parasitoids, if present, were not discernible from the host. X-rays of live, freshly-killed, or freeze-dried individuals would be more definitive.

Parasitoid densities can be expressed in different ways. Apparent parasitism reflects the proportion of hosts attacked by parasitoids and is expressed as a percentage of the total number examined (Miller 1963).

During the life cycle of the spruce budworm, parasitoids attack in sequence and apparent parasitism percentages for various spruce budworm developmental periods can be combined to give aggregate parasitism rates (Dowden and Carolin 1950, Jaynes and Drooz 1952, McGugan and Blais 1959, Blais 1960, 1965, Kemp and Simmons 1976).

Parasitoids of the Spruce Budworm

Approximately 90 different parasitoids, with a variety of life strategies, have been recovered from spruce budworm (McGugan and Blais 1959). Primary parasitoids have been found associated with each immature stage of the spruce budworm. Many of these are exploited by secondary parasitoids (hyperparasites) and facultative hyperparasites. Some of the primary parasitoids are not wholly dependent on the spruce budworm, but find suitable alternative hosts among other defoliating insects. Other multivoltine parasitoids may require an alternate host to complete development. The number of generations per year of parasitoids ranges from one for Apanteles fumiferanae Vier. and Glypta fumideranae (Vier.) to 13-52 for Trichogramma minutum Riley. Multiparasitism occurs when parasitoids of two or more species simultaneously lay their eggs on or in the same host. Superparasitism, where more than one egg is laid in or on the host by one or more females of a solitary species, is a

²/ Bio-mix 9769, BioServ Inc., P.O.Box 15., Frenchtown, NJ 08825.

frequent occurrence in high density spruce budworm populations (McLeod 1977).

Thirty species of parasitoids, representing five Hymenoptera and one Diptera family, were reared from the spruce budworm during the course of this study. Most abundant were members of the Apanteles complex, then Glypta fumiferanae (Vier.), Meteorus trachynotus Vier., undetermined species of Encyrtidae, Charmon gracilis (Prov.), and Apechthis ontario (Cresson). Several hyperparasites were identified. Aggregate percentages of parasitism ranged from 89-98% in the study plots.

Forecasting Spruce Budworm Infestation Intensity and Damage

At a given time, some members of the spruce budworm parasitoid complex are relatively rare while others are common (McGugan and Blais 1959, Miller and Renault 1976). They may act singly, in combination, or in sequence. Some respond to changing host density, and their effectiveness varies as the population size grows (Knippling 1979).

It is not unusual for endemic host insects to have large complements of parasitoids (Force 1974). For the spruce budworm, 10 or more species of parasitoids may be associated with just one larval instar. Some ecologists attribute this degree of species packing to the extreme specialization of parasitoids (Force 1972). Where more than one species is exploiting the same host during the same or different life stages, methods of partitioning host resources are necessary (Price 1972).

On the other hand, a parasitoid that is capable of adapting to changing conditions or controlling hosts over broad geographical ranges has certain advantages (Graham and Knight 1965). The ability to feed on more than one host is beneficial during the collapse period. Then, the polyphagous parasitoid would not suffer from food shortage and higher population levels could be maintained. This advantage enables the parasitoid to retard the subsequent multiplication of the original host at a later time. Clearly, this ability can be modified by other variables, including the reproductive potential of the parasitoid.

Major differences in the abundance and diversity of parasitoids attacking epidemic and endemic budworm populations have been recorded. While the important species of the parasitoid complex associated with epidemic populations appear superficially similar throughout the range of the pest (McGugan and Blais 1959), data from endemic studies indicate that the complex is less predictable when spruce budworm populations are low (Fye 1963, Miller 1963, Miller and Renault 1976).

Continued observation of parasitoid fluctuations through endemic periods can yield

insight and knowledge that may some day foster a management practice that can delay or prevent the next outbreak. Parasitoids could be a powerful predictive tool, providing an index to the spruce budworm population cycle.

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A discussion of the silvicultural practices that can be employed in managing spruce-fir timber type to increase its resistance to the spruce budworm. The silvicultural options identified as being most effective include: shortening the rotation, reducing the fir component, converting to non-host species, and developing a patchwork of age classes.

Introduction

It is well documented in the literature that the application of chemicals as a spruce budworm management tool has its limitations and cannot be viewed as being entirely effective in controlling the insect. Silviculture also fits into this category. Silvicultural practices have long been recognized as a mechanism of reducing losses from a budworm attack, but not as the final answer to control. With the intensification of forest management of the spruce-fir timber type, the potential exists to successfully compete with the insect for the resource.

Essentially, we have reached the point of recognizing the spruce budworm as one of the perennial problems of the spruce fir type that must be shared with regeneration failures, overstocking, deteriorating stands and low-growth rate. Westveld (1953) alluded to this issue when he stated, "All the standard practices that form the repertoire of the practicing forester, ranging from cutting methods to stand improvement and protection measures, must be brought to bear on the problem(s) if the overall (production) goals are to be realized in a reasonable period."

Standard Silvicultural Practices

Uneven-aged Management

The spruce-fir timber type is well-suited for either uneven-aged or even-aged management. There are standard silvicultural practices established for both systems. Spruce and fir are tolerant species capable of regenerating in the shade of an overstory of brush or trees, or in the opening of clearcut areas. Of the two species, fir is by far the most aggressive. Fir seeds much more prolifically than spruce. Fir seedlings develop more promptly, have more rapid root development and seedling height growth. Spruce is weaker, more fragile, and grows slower than fir during the seedling establishment period.

Because fir has this inherent capability of rapid seedling establishment and development and the fragile nature of the spruces, special forestry measures are required to increase the spruce component in a new stand over and above what was present in the old stand. Under uneven-aged management, these special forestry practices are built into the system to favor spruce. By maintaining a continuous tall tree cover, removing the fir in periodic harvest operations and providing a good source of spruce seed, the management system holds fir seedling development in check and compensates for the slow seedling growth of spruce.

Even-aged Management

Under even-aged management, the regeneration method is the installation of a clearcut at the end of the rotation. The success of this practice is dependent upon the abundance of advanced regeneration of spruce and fir. If advanced regeneration is not present, invading hardwoods and shrubs such as mountain maple, hazel, and raspberries take over the site temporarily. It usually takes 10 to 15 years for the softwoods to overcome this brush stage and become fully established. Clearcutting without advanced regeneration favors fir and less desirable hardwood tree species such as red maple and poplar. In many cases, the site develops into a mixed stand of hardwoods and softwoods rather than a pure stand of softwood. In some instances, this can be a desirable change especially if the mix of species includes a representation of the more desired hardwoods such as white and yellow birch, white ash, and sugar maple on the upland secondary sites.

One of two harvesting methods can be used to correct a deficiency of advanced regeneration: (1) a two or a three cut shelterwood, or (2) a strip cut with strips at least as wide as the tallest trees or up to 150+ feet wide. Both methods provide excellent site conditions for regeneration and result in a high representation of spruce in the new stand--up to a 30% increase. Additionally, a time loss of 10 to 15 years to the brush stage is avoided for the most part.

Silvicultural Guide

Prescription guidelines for managing stands of spruce-fir are well established in the silvicultural guide (Frank et al 1973). Specifically, early thinning is recommended in sapling stands when they are about 10 feet in height. These early thinnings or cleanings in stands developed after a shelterwood cut can have the greatest impact on composition change. Experimental trials on the Penobscot Experimental Forest, Orono, Maine, have demonstrated an increase in the spruce component of over 50%. Although this degree of change cannot be expected in all cases, it does illustrate the importance of the measure in altering composition. Even with its potential, however, cleaning young stands is a practice rarely installed, mainly because of the high cost of the measure.

In pole and sawtimber stands, commercial thinning is recommended when stocking is above the halfway mark, between A and B levels, of the stocking chart (see Appendix). The chart identifies stands between the A and B levels as adequately stocked. Stands above the A level are overstocked; those at the C level are understocked, but represent a point where ten years of growth should raise the stand to the B level. B level represents minimum stocking for maximum individual tree growth. Since the intent of thinning young even-aged stands is to foster rapid growth of the individual crop trees while fully utilizing site capacity, reducing the stand to the B level is the intended thinning goal.

Silvicultural Options To Reduce Vulnerability

These clearly defined management strategies are directed toward timber production of the spruce-fir timber type without the interference of the spruce budworm. To compete with the budworm, however, adjustments must be made in these practices with the expectation that these alterations will not seriously reduce timber production. The intent here is to identify silvicultural options that are considered most effective in growing the resource at the lowest possible level of vulnerability, with the main thrust being to: shorten rotation, reduce the fir component in spruce-fir stands, convert to non-host species where the opportunity arises, and develop a patchwork of age classes.

Uneven-aged Management

Uneven-aged management of spruce-fir has many attributes that are highly appealing to the non-industrial private landowner. It is a system that provides periodic income, maintains a continuous tall tree cover and provides a minimum amount of disturbance during harvest operations. Aesthetic values are protected throughout the entire period of management.

Even with all these points in its favor, uneven-aged management needs a critical evaluation as to its effectiveness in reducing vulnerability. The system is man-made, requiring a high degree of professional input and a lengthy time span to develop the uneven-aged structure. Additionally, severe infestations have converted many uneven-aged stands to even-aged in a matter of a few years, undoing the professional work of many years. These are factors which tend to cause the system to be looked on by many professionals with disfavor. Baskerville (1975) addressed this issue. He stated, "The net result of the practice of selection forestry would be the preservation of large areas of mature (or near mature) forest which would be ideal for budworm survival. It would appear that the concept of the selection forest has no place in management for control of the budworm." With these points considered and the degree of uncertainty that exists, it would indicate that research in this area would rate top priority.

Even-aged Management

Although less appealing aesthetically, even-aged management is without these critical limitations. It is easy to apply and has proven to be most effective in reducing vulnerability. The system provides the landowner with the best options such as converting to pure stands of hardwoods or mixed stands, or converting to white pine, black spruce, and other non-host species by planting.

It is the opportunity to breakup spruce-fir stands into a patchwork of age classes rendering each subunit of the stand to a lower level of vulnerability. Even-aged management provides for the rapid development and growth of each age class unit--seedlings, saplings, poles and sawtimber.

Conversely, uneven-aged management favors rapid sawtimber growth, with less than maximum growth of many of the smaller size classes. This is because the saplings and poles are below the main crown canopy and many of them are not free to grow and under competition stress, causing them to be less vigorous. This subjects the smaller size classes to greater danger of loss by the spruce budworm.

Rotation Age

Most spruce-fir stands are presently being managed rather extensively on a 70-90 year rotation or longer. The literature suggests that the most important step to reduce vulnerability is to shorten the rotation to age 50 (Hatcher 1960). This requires the intensification of forest management practices so that trees are free to grow without competition throughout the entire rotation.

The most critical first step in intensifying management of natural stands is cleaning young sapling stands. With this practice, followed by a thinning of pole stands, the growing of a crop of pulpwood and small sawtimber in 50 years is within the realm of possibility. Without the cleaning measure, it is questionable whether trees can be grown to sawtimber size in this short period of time.

Conversion To Non-host Species

Conversion to hardwoods is an option that should be considered, particularly on the best upland sites. If desirable hardwoods are present in the stand or in the surrounding stand, this is a promising, viable option. To avoid the invasion of less desirable hardwoods, red maple and aspen for example, a two cut shelterwood can be employed to bring about the conversion to more desirable hardwoods--sugar maple, yellow birch or white ash. If paper birch is present and paper birch is desired, clearcutting the area leaving behind birch seed trees would be the appropriate method. If desirable hardwood are not present, the obvious choice would be to manage for spruce-fir.

Planting of non-host species such as white pine, red pine or black spruce is a strategy that needs to be employed to a greater extent. Plantations can serve as buffer strips to breakup large continuous areas of spruce-fir forests. Over a period of 50-60 years, plantations can make a significant contribution to the forest industry without any need of protection from the spruce budworm.

Patchwork Of Age Classes

The breakup of spruce-fir stands into a patchwork of different age classes is a management strategy "most likely to succeed" in reducing vulnerability (Baskerville 1975). Even though it is more appropriate and effective on a regional basis, the starting point is the individual landowner. This is a concept that is easily understood by the landowner and easily sold to him. Also, the strategy has the potential of serving as the key to implementing forestry practices. If each woodlot is approached with the intent of breaking it down into smaller units, then the forestry practices needed for each unit would be within the grasp of the landowner. The large job would be reduced to several small jobs.

To illustrate, assume a landowner has 40 acres of an even-aged sawtimber stand of spruce-fir. This tract can be broken down into four 10-acre units with a long-range goal of: 10 acres in regeneration stage; 10 acres in seedling and sapling stage; 10 acres in young poles; and 10 acres in large poles and small sawtimber. The immediate prescription towards meeting this goal would be to clearcut a 10-acre block. If advanced regeneration is not present, plan on planting. On another 10 acres, install the first cut of a two cut shelterwood to increase the spruce component or to convert to sugar maple. On the remaining 20 acres, thin to the B level favoring spruce.

The next entry into the stand in 10 or 15 years can include: 10 acres of cleaning in sapling stands; 10 acres of shelter trees can be removed; 10 acres--the first cut of a shelterwood can be applied; 10 acres--can be thinned again. In a period of about 30 years, this 40-acre tract can have a well-balanced age structure that can be maintained indefinitely.

This concept can be applied to all existing condition classes, including pure stands of pole timber or stands made up of scattered patches of seedlings and saplings, poles and sawtimber. In each case, it is essential to break the area down into smaller units, possibly no smaller than 5 acres in size, followed with the removal of trees to create the even-aged structure for each unit.

Harvest Methods

As the intensification of forest management activities is essential in developing less vulnerable spruce-fir stands, harvest methods of clearcut areas must be adjusted to accommodate forestry efforts. The planting of cleared sites or the cleaning of young stands requires ease of access and movement of personnel and equipment on the

site immediately after the harvest, or long before the logging slash has decayed. Whole tree harvesting methods applied to clearcut areas would remove the accumulated litter of tops and branches, making the site much easier to work on and at less cost.

Such a method of harvest requires the piling of slash at the landing site, but this material can be easily disposed of by chipping or burning. Certainly, this method is preferred to leaving the tops on the site where they hinder work and increase cost of accomplishment for many years.

Protection

The foregoing are the silvicultural tools the land manager has in diminishing the impact of the spruce budworm. They are designed to develop fast, vigorous growing trees capable of producing an acceptable crop in 50 years or less, to produce stands with more spruce than fir, and to provide the encouragement to convert to non-host species where conditions permit. The closer the landowner comes to matching these conditions, the greater impact can be expected in favor of the resource. The resource is conditioned to withstand and recover from a budworm attack. Additionally, in this situation, the landowner is provided a choice of spraying or not spraying, without the complete loss of his resource if he chooses the latter.

As protection must be an integral part of management, it is essential that field foresters be trained to identify stands that need protection, stands that need to be salvaged, stands that need no protection, and made aware of the implications of not applying protection measures. Hazard indicators, such as top kill, should have some meaning as to risks involved and management action necessary. Only through this basic knowledge of the spruce budworm's actions, along with silvicultural skills, can the field forester be effective in growing spruce-fir timber in competition with the budworm and offer the landowner the best technical advice.

Conclusion

It is generally agreed that as more of the spruce-fir timber type comes under management and a diversity of age classes has been created on a wider scale, a more resistant forest will be created. Presently, there is a critical shortage of reliable data that can pave the way of removing many uncertainties in managing the timber type continuously being exposed to the spruce budworm. A concentrated long-range research effort to evaluate various silvicultural practices is long overdue.

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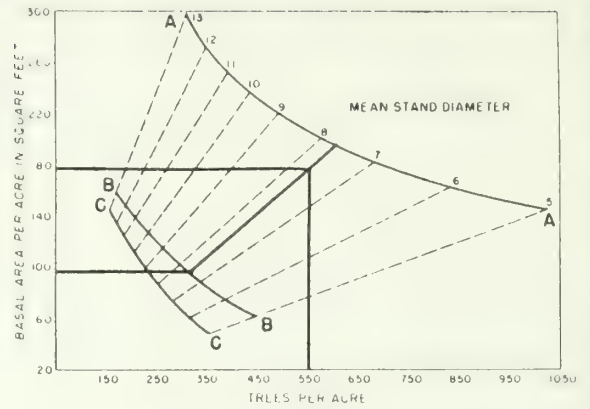
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Appendix



Stocking chart for even-aged spruce-fir, based on the number of trees in the main canopy, average diameter, and basal area per acre. The area above the A-level represents overstocked stand conditions. Stands between the A- and B-levels are adequately stocked. Stands between the B- and C-levels should be adequately stocked within 10 years or less. Stands below the C-level are understocked. (Frank et al 1973).

To use the chart, obtain from cruise data the average number of trees and basal area per acre. Plot the two values on the stocking chart to determine the recommended level of management (B level). For an example, a stand of spruce-fir averaging 550 trees and 180 square feet (ft²) of basal area intersects on the stocking chart below the A line. From this point, follow diagonally, parallel to the nearest broken line of mean stand diameter and mark the point at which the B line is intersected. From this point, draw a horizontal line to the vertical ordinate for the basal area at this level (180 sq ft). The mean stand diameter is about 7.7 inches DBH or the point at which the A line is intersected.

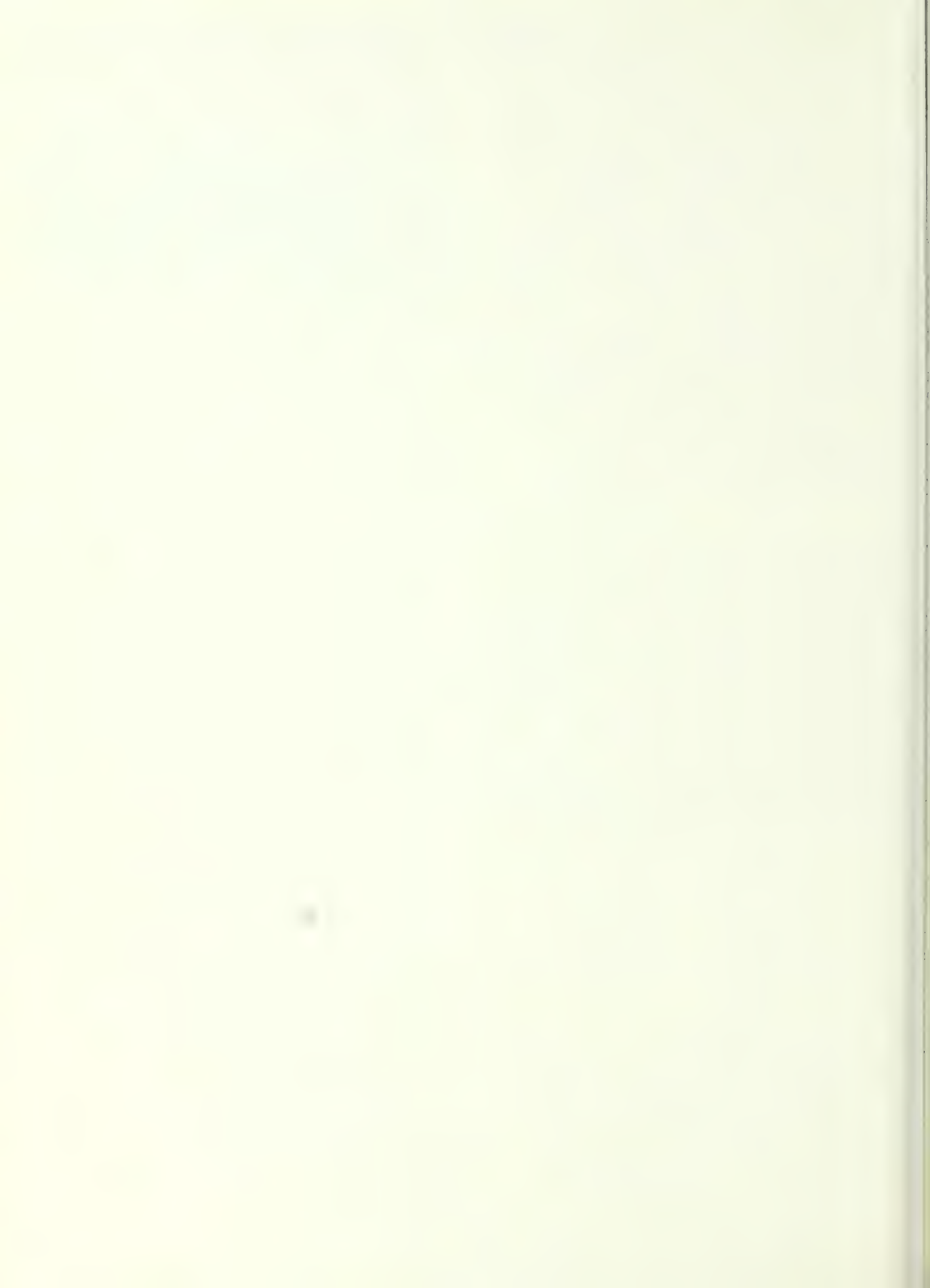
MINIMIZING IMPACTS OF FUTURE SPRUCE BUDWORM

OUTBREAKS

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St. Regis timberlands in Maine are presently experiencing extreme levels of spruce budworm populations which are impacting balsam fir, eastern hemlock and the spruces. Pest management strategies are discussed which will minimize both the present and future impacts of spruce budworm populations.



Introduction

Between 1976 and 1979, the known epicenters from which the current spruce budworm outbreak originated in Quebec were studied and compared. One of the major conclusions derived from that study, and reported by Hardy *et al.* 1983, was that the outbreak gained its initial momentum in meridional forest associations where host-species were outnumbered by non host-species and non boreal species. The epicenters were further characterized by severe ecological perturbation which promoted the establishment of pioneer species and ultimately an abundance of fir and spruce. The same methodology was later applied to areas outside Quebec where spruce budworm infestations are a major concern. Manitoba, Ontario, New Brunswick and Maine were included in this portion of the study.

Methodology

Assistance was first sought from local provincial and state authorities in order to pinpoint the year and location(s) of appearance of new outbreaks in each state or province. Thus, the expertise of Mr. Hildal, (Manitoba) G. Howse (Ontario), E. Kettela (New Brunswick), and H. Trial (Maine) supplemented the use of defoliation maps. To be considered an epicenter, an incipient infestation had to be distant from any ongoing outbreak by at least 150 km, or known as a lasting residual outbreak, such as those of Chatham and Nashwaak, N.B. and Oxbow, Me. The epicenters were further expected to expand geographically from year to year. A total of 22 such epicenters, including 7 from Quebec, were identified. Among those, four were to the same general area in Ontario and later called Cobden I, II, III and IV. A control plot, where no sign of advanced budworm activity had been recorded, was added in a red spruce association in Southern Quebec, to compare the vegetation types. This was later referred to as Quebec Sud. A vegetation survey was carried out in each epicenter according to the methodology described by Brawn-Blanket (1932) and Hardy *et al.* (1983), to provide a qualitative and quantitative description of the vegetation of the various strata. A total of 617 1/100 ha sample plots were thus established. A map showing the major climatic forest associations was also prepared by integrating the various forest classifications available for the area under study.

The mean annual and summer (April to August) temperatures of each epicenter were determined by reference to nearly meteorological stations in similar situations. From these data, the mean annual and summer temperatures were calculated

for the whole region and the smallest variance which included the warmest and coldest epicenters was used to construct annual and summer isotherms for the region.

Results

The buffering effect of the sea on the climate of the maritimes is apparent in Figure 1, where the mean annual isotherm of 1.2°C swings deeply north along the north shore of the St. Lawrence river and the gulf of St. Lawrence. The opposite effect is observed in more continental western Ontario and Manitoba. In this case, the summer temperatures isotherm, converted into day-degrees above 5°C, goes deeply north in response to the high summer temperatures observed in these longitudes, while cold winter temperatures bring the annual isotherm to a more southern location. Since the physical conditions prevailing during both summer and winter are equally important for budworm survival, both extremes were limiting. Budworm survival was limited in the east by inadequate summer heat and in the western part of the range by extremely low winter temperatures. The result is shown in Figure 2 which, in our opinion, best describes the preferential thermal zone of the spruce budworm.

On the other hand, when we consider the position of the epicenters by reference to forest associations, it can be seen that the vast majority belong to a northern hardwoods association, with a configuration almost identical to that of the isothermic corridor previously defined (Fig. 2). A closer look at the vegetation recorded in the epicenters (Table 1), confirms the universal presence of meridional species along with numerous pioneer species and an abnormal amount of host-species.

These findings suggest that the current outbreak gained its initial momentum in a rather clement physical environment normally occupied by meridional forest associations, which had been gradually invaded by host-species in reaction to various forms of perturbation such as, harvesting, forest fires, and natural reforestation of abandoned farm lands. Although our data on forest composition are minimal, changes in the forest composition should not be underestimated since they are confirmed by various other sources. For example, Bonnor (1982), in a synthesis work of Canada's most recent forest inventory, shows that the better part of the maple associations of eastern Canada are now typed as mixed wood, suggesting the recent invasion of these hardwood associations by softwood species. Similar indications were also given by recent vulnerability ratings of New Brunswick and Nova Scotia forests, as well as Quebec (Mac Lean 1982; Blais *et al.* Archambault 1982), which indicate that the most vulnerable forests are those of central N.B. and the St. Lawrence valley in Quebec. The abundance of host-species being the major factor along with general climatic condition to determine vulnerability, it appears quite clear that host-species have become more abundant in those predominately hardwood associations of central N.B. and southern Quebec.



Figure 1.--Annual and summer isotherms corresponding to the narrowest corridors that include the warmest and coldest epicenters

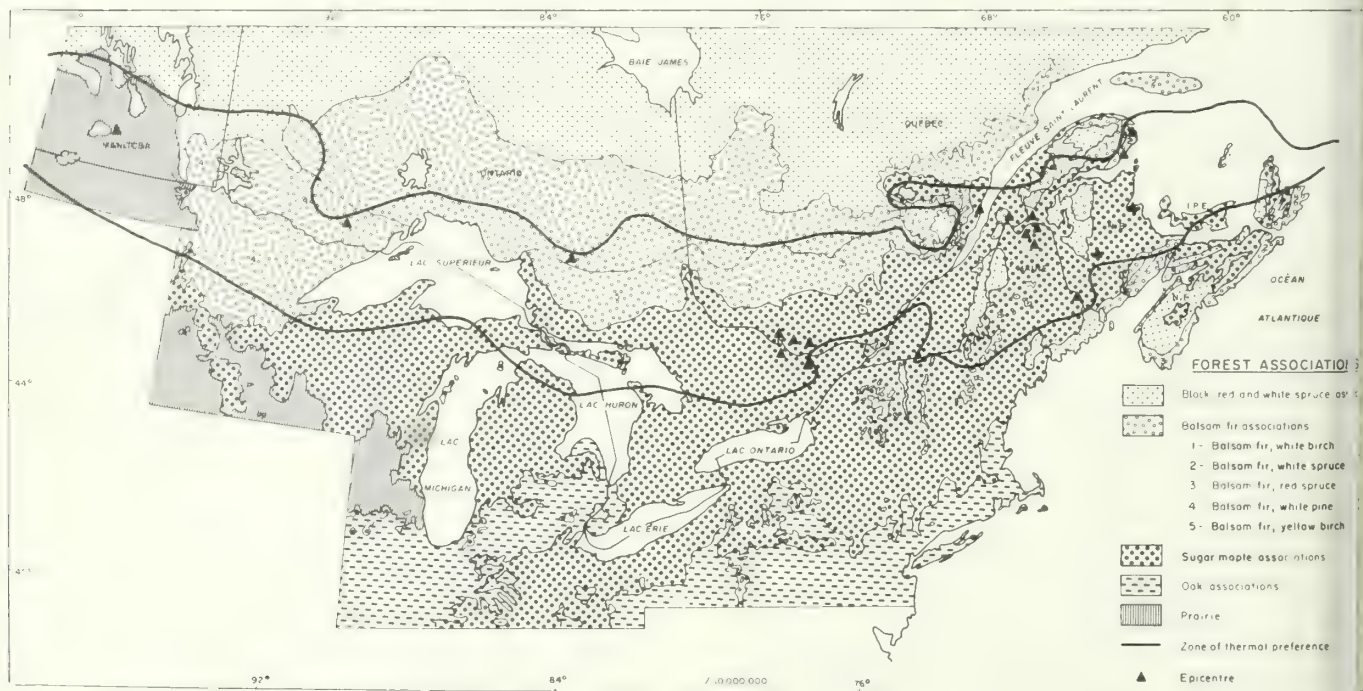


Figure 2.--Zone of thermal preference of the spruce budworm in eastern North America in relation to the major forest associations

Table 1. Relative Abundance of the Principal Tree Species Found in the Epicenters.

	X: abundant species	: presence	1: Host species																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																
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Discussion

The pattern observed at the beginning of the current outbreak differs quite drastically from usual beliefs about the initiation of a spruce budworm outbreak. Instead of seeing the outbreak originate from vast boreal regions of mature spruce-fir forest, this outbreak acquired its initial momentum in a more southern environment, where host-species are outnumbered by non host-species and where over-maturity was not a characteristic of spruce and fir. These apparent contradictions, coupled to the fact that most recent outbreaks have been more widespread, of longer duration and appeared at shorter intervals (Blais, 1983), are indicative of a new equilibrium between the major components of this ecosystem. However, when these discrepancies are viewed within the framework of the concept of "zones of abundance" first proposed by Cook (1929), the behavior of the current outbreak becomes more easily understandable. According to Cook, the range of an insect is divided into three zones, the principal characteristics of which appear in Table 2.

Table 2. Principal characteristics of Cook's concept of zones of abundance.

<u>Zones of abundance</u>	<u>Environment</u>		
	<u>Climatic</u>	<u>Biotic</u>	
		<u>Food</u>	<u>Predation</u>
Normal	Optimal	Rare	High
Occasional	Acceptable	Abundant	Low
Possible	Unsuitable	Rare	Very low

Within the zone of normal abundance favored by optimal physical conditions, the equilibrium is normally maintained either by the absence of a abundant source of food and habitat or by the effectiveness of parasites and predators to respond rapidly to a population change of the pest. Most outbreaks should start within the limits of the zone of normal abundance, but should be of short duration due to the relative scarcity of food and the biological resilience of this environment.

Outbreaks can also be initiated within the zone of occasional abundance, but such an event should be less frequent since it will have to happen within the confines of a particularly suitable microenvironment, or after a period of climatic release which would make the physical conditions in this area comparable to those normally experienced in the zone of normal abundance. On the other hand, once an outbreak is initiated in this zone, the abundance of food and the lesser predacious activity will favor outbreaks of longer duration.

Finally, it is possible for an outbreak to originate in the zone of possible abundance, but this event will be of lesser importance since both the physical and biological conditions are not favorable to the insect. Under the conditions prevailing in the zone of possible abundance, outbreaks should be rare and of short duration and would have to be fueled by incoming populations from outside areas.

This brief description is not without parallel with the current spruce budworm outbreaks. The northern hardwood associations where this outbreak was first observed correspond almost perfectly to the zone of normal abundance. Favorable climatic conditions and relative scarcity of food are intrinsic to this zone, while a high biological activity could be inferred by the diversity of this environment. The southern boreal forest, which contains the white spruce-fir-birch association is, for its part, closely linked to the zone of occasional abundance. These associations provide an almost inexhaustible source of food. Climate has often been reported as responsible for the collapse of outbreaks in this area and parasitic activity has always been considered marginal with respect to its influence on the course of an outbreak. Finally, the black spruce associations of the northern boreal forest would correspond to the zone of possible abundance, along with the meridional hardwood associations where hickory is a normal component of the forest associations.

Forest management practices should be reviewed accordingly and a hard look should be given to our current harvesting and reforestation practices which tend to increase the spruce and fir content of the meridional forest. If drastic steps are not taken in this direction, the future will follow the trend of the past fifty years and spruce budworm outbreaks will become an integral part of the biotic balance.

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LANNING NOW TO REDUCE, POSTPONE OR PREVENT THE
XT SPRUCE BUDWORM OUTBREAK"

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Ten characteristics of outbreak patterns
recognized in Ontario infestation maps for
the period 1947-1983, for which explanations are
available in recent scientific literature. A
related long-term strategy of outbreak prevention
proposed for implementation internationally
(Canada, U.S.A.) over the next decade.

Introduction

Recently I have had the opportunity to up-
date my knowledge of the scientific literature on
the spruce budworm and to step back after 35
years of close association with research and sur-
veys to analyze and describe changing patterns of
infestation (infestation dynamics) reported in
the Province of Ontario.

Yet this assigned topic was approached with
a degree of apprehension for three reasons.
Firstly, because the insect has created such an
array of sensitive, chronic and firmly entrenched
problems in North America. Secondly, my main
source of information consists of pooled monitor-
ing data with a heavy mix of associated observa-
tions not regarded as sound proof. My data are
much more than anecdotal but on the other hand
they are not strictly speaking thoroughly scient-
ific. Thirdly, the original approach for dealing
with spruce budworm emergencies in Canada in-
volved both research and coordinated surveys, and
not conceptual models concerning system function
which seem to have emerged from theoretical research
rather than from observed conditions. As a con-
sequence, I have a great deal to cover in a
single presentation.

The literature update has confirmed my
impression that so far man's approach to the spruce
budworm problem has of necessity been largely
defensive in nature, i.e., responding to develop-
ments without influencing the dynamics of infes-
tations in positive ways. There are numerous
examples: monitoring and evaluating situations,
protecting vulnerable forests of high value,
establishing biological relationships, measuring
impact, learning how to live with the budworm,
etc.; all essential pest management activities--
not reacting to events more than influencing
them.

So far only two attempts have been made to
activate outbreaks and the results were of
qualified success in both instances. The first
was in the Kedgwick Lake area of Quebec (Blais
1963) and the second was begun near Burchell
Lake, Ontario (Sippell, et al. 1969) and con-

tinued over 9 years before being abandoned in
1977 (Howse, et al. 1979). In other instances,
spruce budworm infestation was virtually elimi-
nated from stands in part of an operational spray
program (Dimond, 1976), but the objective was
different.

The research community is continually being
challenged to more ably express its genuine
interest in controlling the spruce budworm by
discovering and promoting more effective outbreak
prevention strategies.

This paper introduces to this workshop some
new entomological concepts, based on 37 years of
intensive surveys and infestation history, and
asks as well as suggests how they may be used to
develop an international strategy to reduce,
postpone or perhaps even prevent future outbreaks
from occurring through at least part of the range
of the spruce budworm in North America. It
introduces more of the "learn by doing" approach
to outbreak prevention. Hopefully it will also
change the focus of our mind's eye in thinking
about and discussing a more influential plan of
future action in managing this major forest pest.

Materials and Methods

Beyond cited literature references, the
information presented on infestation patterns and
change is taken from the reports and files of the
Forest Insect and Disease Survey (FIDS) project
at the Great Lakes Forest Research Centre in
Sault Ste. Marie. Liberal use is made of their
maps published annually in numerous reports such
as Meating, et al. (1982), Howse et al. (1983),
and Applejohn and Howse (1982). Observations of
field conditions throughout the province were
acquired through contact with and the assistance
of many staff members of the Centre, mainly those
associated with the FIDS project for which the
author was project leader for 25 years.

The total area to which historical observa-
tions apply (Ontario) covers 891,000 km² (343,000
sq. mi.) of which almost half 430,000 km²
(165,000sq. mi.) are forested. In the interest
of simplicity, the term "infestation" as applied
to this large land mass refers to the condition
in which populations of spruce budworm are or
have been of sufficient numbers in any year to
cause detectable feeding damage when viewed from
the air.

Analysis

General information is available as to
where infestation has occurred each year in
Ontario since 1920 or so. But each year since
1947 the Canadian Forestry Service through the
cooperation of the Ontario Ministry of Natural
Resources (formerly Ontario Department of Lands
and Forests) obtained complete and detailed
information on areas affected. The series of 37
annual infestation maps being flashed on the
screen for each of the years 1947-1983 have been
vital to this general and long-term study of

natural infestation dynamics. "Natural" is used here in the sense that Ontario outbreaks, by and large, have been allowed to run their course uninfluenced by widespread aerial spraying.

Ten Characteristics of Ontario Outbreaks

Ten generalized and somewhat interrelated characteristics of infestations in Ontario are compiled and described, some of which are newly recognized, some have long been recognized but explanation has been lacking or imprecise, others either remain to be more fully elucidated and conceptualized in published form, and still others must be more adequately demonstrated in future series of annual infestation maps. For most of the 10 characteristics numerous examples could be given, however in the interest of time and space one or in a few instances two are presented by way of illustration to help clarify.

C-1. Over the long term, the extent of infestation fluctuates to the extremes.

A comparison of the infestation map for 1964 (Fig.1) when less than 40 ha (100 acres) of infestation was recorded, with the map for 1981 (Fig. 2) showing a gross area of infestation equal to 18 million ha (45 million acres) pro-

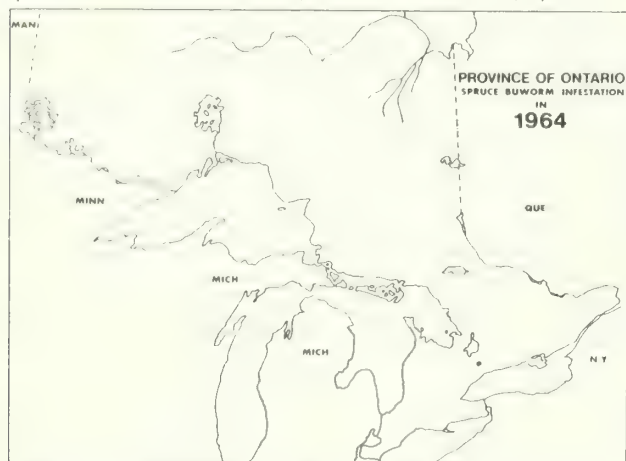


Figure 1. Infestation map for 1964.



Figure 2. Infestation map for 1981.

vides a striking illustration of the wide differences that occur in infestation extent over time. Moreover, population levels may become extremely low over large areas during an inter-outbreak period so as to be considered virtually absent. Figure 3 shows the results of beating samples, i.e., 20 samples of larvae beaten from a m^3 volume of foliage over a m^2 tray, 2 from each of 10 trees and timed for fifth and sixth instar larvae (L_5 , L_6).¹ In a scattering of 15 points within an area of roughly 60,000 km^2 (23,000 sq. mi.) not one larva was collected by beating in any of the 5 years of sampling, 1969-73. This is not to imply that the insect became temporarily extinct however, since an occasional larva or adult was collected in the same area and time-frame by other methods including search techniques and light traps. But clearly the level of incidence during the 5-year period was extremely low.

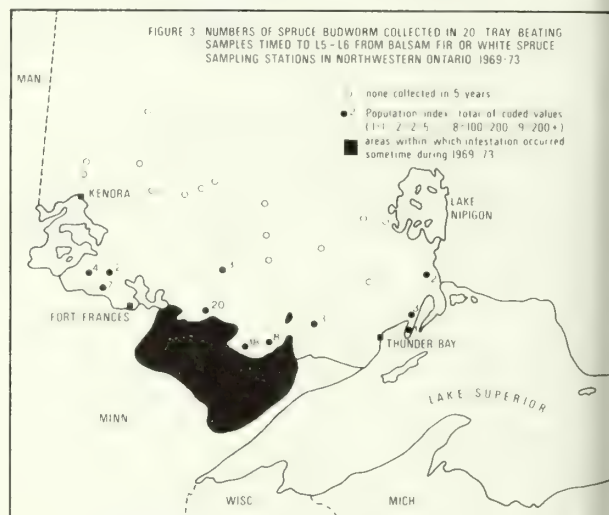




Figure 4. Infestation map for 1966 including northern Minnesota and western Quebec.

3. Between outbreaks, numbers generally vary inversely with distance from infestation.

Evidence is becoming overwhelming that the migration and immigration of moths carrying a partial complement of eggs as described by Greenank, Schaefer and Rainey (1980) are influential forces in infestation movement and change during outbreak. Sanders (1977) reported that the dispersal of egg-bearing females takes place only at high population densities. Because moths biologically cannot differentiate the size of infestation of which they are a part, it must be assumed that moth populations behave in a similar manner whether they represent a small heavy infestation between outbreaks or part of a major outbreak.

The results of the m^2 beating-tray sampling done in northwestern Ontario between 1969 and 1973 (Fig. 3) show that, in general, population levels decrease with increasing distance from areas of infestation which in this instance were located in the vicinity of the International Border between Thunder Bay and Fort Frances. However it should be pointed out that determinations of population trends influenced by wind direction can be expected to be imprecise especially when moth flights take place after dark and cannot be substantiated by direct observation.

4. Forests show a degree of natural resistance to low levels of moth invasion.

The influx of moths from infestations to spruce-fir forests which are supporting very low numbers of spruce budworm must occur from time to time. Evidence of such occurrences and the subsequent result is available again in the m^2 beating tray samples, Table 1. Marked increases in numbers collected in 1971 at four locations in the Kapuskasing District following 2 years of nil returns reflects a probable influx of moths

Table 1. Numbers of spruce budworm collected in beating tray samples, 2 per each of 10 trees, 1969-73, in Kapuskasing District, Ontario

Location \ Year	1969	1970	1971	1972	1973*
Gill Twp	0	0	11	7	2
Fergus Twp	0	0	7	1	2
Howells Twp	0	0	2	2	0
Tenton Twp	0	0	14	8	0

* year of spring frost

in 1970 from extensive infestations 80 km (50 mi.) or more to the south. Resistance is evidenced by a consistent decline in numbers for the subsequent 2 years. Eventually however a large part of Kapuskasing District did become infested, presumably as the result of repeated inflows associated with a northward advancing front. The resistance indicated is probably more in the form of predacious birds and arthropods rather than insect parasitoids specific to spruce budworm, because before 1971 hosts upon which parasitoids depend for survival were rare. Populations that surge upwards as the result of moth influx in circumstances of this kind can be expected to show particularly low incidences of parasitism since the parental stock of parasitoids is left behind during dispersal--a hypothesis currently being tested.

C-5. New infestations appear to be the result of moth influx from active infestation.

Two characteristics are common to new infestations originating by moth influx. During the first year, noticeably greater damage occurs on white spruce in stands where both white spruce and balsam fir are present, followed in subsequent years by damage on both species. Secondly, defoliation patterns indicate an abrupt rise in damage levels, i.e., markedly higher levels of defoliation on the current new shoots than on shoots of previous years.

Observations of the initial stages of new infestation are all too uncommon but when made usually provide evidence that points to moth influx as being the source. Over the 37-year history since 1947 only three valid case histories of outbreak eruption were detected, all three of them in 1967 (Fig. 5). All three showed evidence of dependence on active infestation located elsewhere: the northwestern Ontario infestation western Ontario infestation linked by association with infestations in northern Minnesota; the Ottawa valley possibly associated with the 150 km² (60 sq mi.) infestation near Grand Mere, Quebec (Martineau and Oulette 1967) located some 290 km (180 mi.) to the east, or some other unknown source; and the Chapleau infestation from what appeared to be surviving remnants of a previous outbreak in the form of small active infestations.

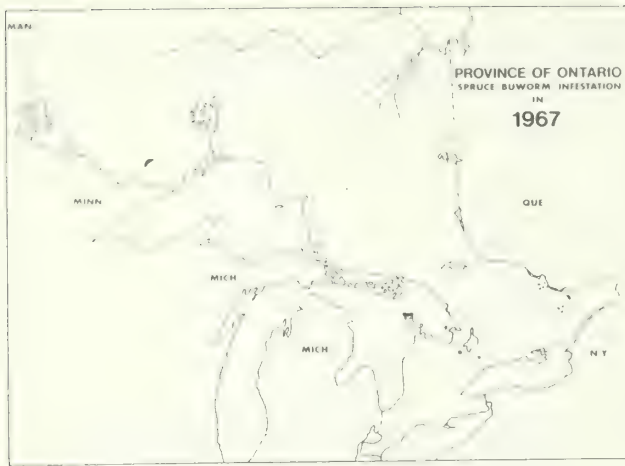


Figure 5. Infestation map for 1967.

So far we have considered the initiation of outbreaks since 1947. In the 15-year period previous to 1947 only two outbreaks erupted namely, the Lake Nipigon and Lac Seul outbreaks. A third outbreak had occurred continuously in northeastern Ontario since 1921. Recent enlightenment concerning the considerable distances over which moths can disperse, such as from New Brunswick to Newfoundland (Dobesberger et al. In press), a dispersal distance of 600 km (370 mi.), will not permit me to rule out the suggestion that both earlier outbreaks (Lake Nipigon and Lac Seul) could have originated through moth dispersal. The probable source would have been the older northeastern Ontario outbreak which in 1943 (Fig. 6) had reached its peak and lay approximately 320 km (200 mi.) from Lake Nipigon and 560 km (350 mi.) from Lac Seul.

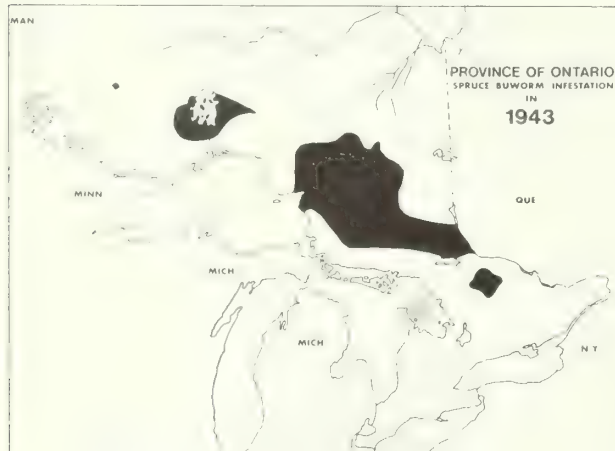


Figure 6. Infestation map for 1943.

C-6. Infestation once initiated tends to spread, and give rise to new infestation in the direction of the prevailing winds.

Historically the tendency for infestation to spread eastward and southward has been well known. This trend has been evidenced both in the

extension of infestation boundaries, and in the appearance of separate new infestations beyond the boundaries of current infestation. The infestation maps for 1949, 1952, 1955 and 1958 illustrate the results of this trend in northwestern Ontario in the direction and magnitude of infestation development as shown in Figures 7, 8, 9 and 10. In contrast, the spread of an outbreak

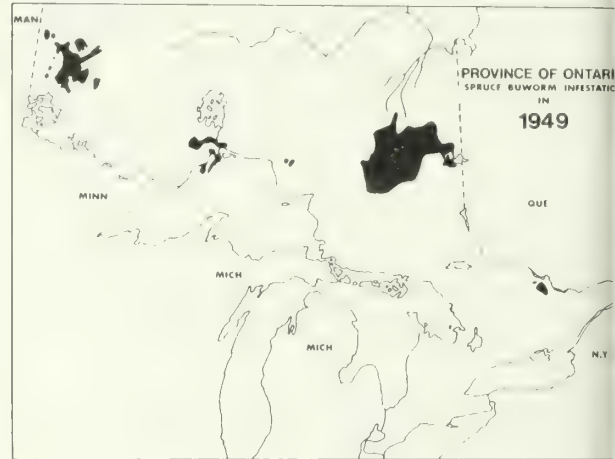


Figure 7. Infestation map for 1949.

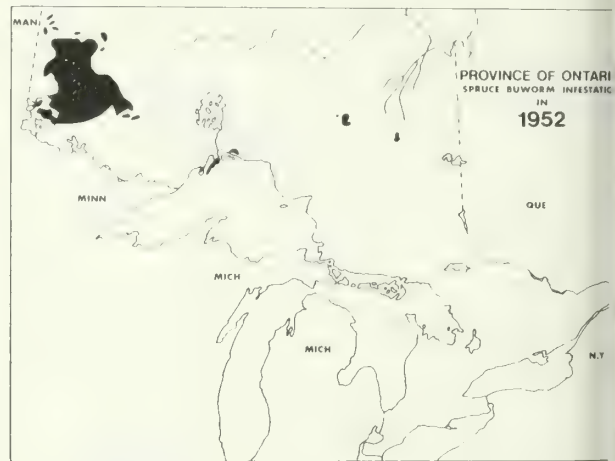


Figure 8. Infestation map for 1952.



Figure 9. Infestation map for 1955.

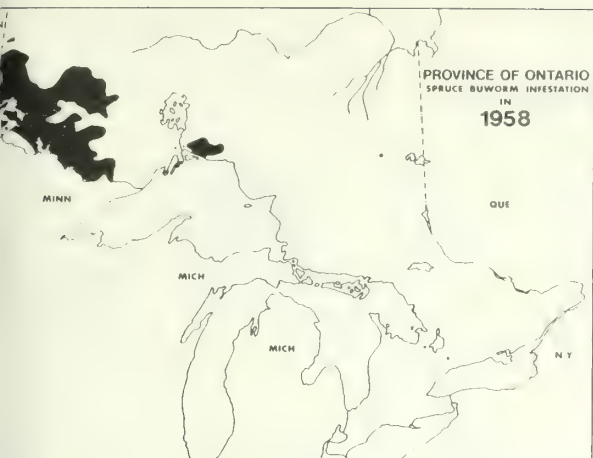
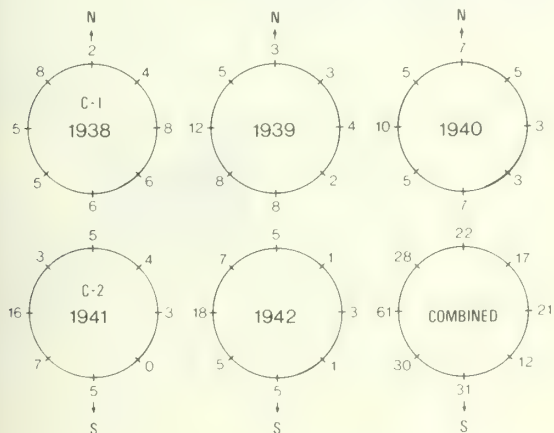


Figure 10. Infestation map for 1958.

wards the northwest has usually been slower and involves shorter distances. It has long been assumed that this southeastward shift was the influence of prevailing NW winds on the dispersal of both small larvae and moths.

This characteristic, C-6, though true in a general sense, can be misleading as shown in the example that follows. During an investigation of possible sources of the early Lake Nipigon and Lac Seul infestations discussed under C-5. I examined wind data¹ from three weather stations in northern Ontario, Sioux Lookout, Thunder Bay and White River (Fig. 11). Overall, evening

FIGURE 11. SUMMARY OF WIND DIRECTION FREQUENCIES BY 8 COMPASS POINTS RECORDED AT 2100, JULY 1-15, 1938-42, AT THREE NORTHERN ONTARIO WEATHER STATIONS: WHITE RIVER, THUNDER BAY, AND SIOUX LOOKOUT



ds at the time of peak evening moth flight (2000) during the period July 1-15, the most probable period of moth activity for the years 1938-42, revealed prevailing westerlies, as shown in the combined data for all 5 years. However

Courtesy of the Climatological Archives Unit, Atmospheric Environment Service, Environment Canada, Downsview, Ontario.

wind directions were anything but consistent and during the period of moth flight in the summer of 1938 were frequently from the east and south, the direction of the extensive northeastern Ontario outbreak referred to earlier. Information on the timing of moth flights and its geographic variation is a prerequisite for more precise studies of infestation dynamics so that the proper data on evening wind directions as recorded by weather stations can be analyzed and influences interpreted.

In summary, C-6, though generally true, must be applied with extreme caution. Prevailing winds merely identify the most frequent direction of winds and certainly are not the only winds that influence moth dispersal or change in infestation borders.

C-7. Infestations that develop in forest types of low vulnerability tend to be short-lived.

One feature of infestation dynamics which reveals in a most convincing way the influence of moth dispersal is the sudden appearance of infestation over large tracts of non-vulnerable forest type in which host trees are scattered. A moth flight on July 11/71 which invaded southern Ontario from the north and east and which gained public attention by invading the city of Toronto, gave rise to damage in 1972 to ornamental host trees throughout a large agricultural zone of southwestern Ontario. Numbers gradually tapered off during the subsequent two growing seasons. Another striking example is the extent of infestation on spruce growing along rivers flowing into James Bay in 1980, Figure 12. It is diffi-



Figure 12. Infestation map for 1980.

cult to imagine how these infestations could possibly have arisen in an area where the cover type is predominantly bog or tundra except through the influx of egg-laden moths from the south. These infestations reappeared in 1981 but not in 1982.

C-8. The intensity of infestation once initiated is governed by stand character and climate.

A vulnerability index system developed by a Canadian Forestry Service Working Group led by J.R. Blais and of which the author was a member uses inventory data and climate ratings. The vulnerability ratings were applied successfully to forest management units in Quebec (Blais and Archambault 1982) and in New Brunswick-Nova Scotia (MacLean 1982). The system could not be extended to Ontario because data on stand age were unavailable, yet there is clear substantiated evidence that infestation intensities reach their highest levels where mature balsam constitutes the major stand component, and that a relatively small area of undesirable stand character and climate for outbreaks exists in Ontario where infestation has declined prior to the onset of appreciable tree mortality. Generally these areas are located north of 50°N Latitude across northeastern Ontario and north of 52°N Latitude in northwestern Ontario as depicted by maps of cumulative areas of host tree mortality, Sippell (1983), see also Figure 13.

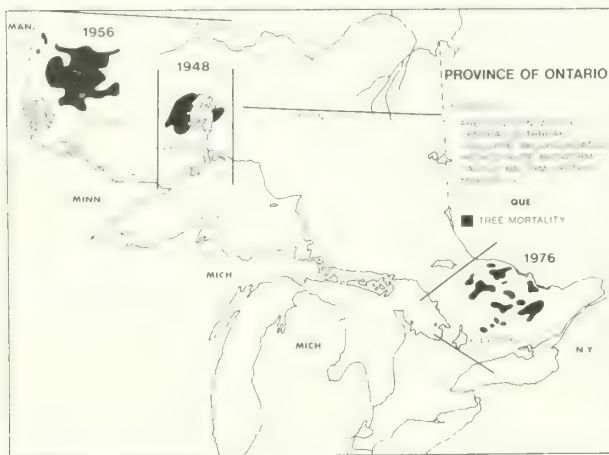


Figure 14. Infestation map for 1972.



Figure 15. Infestation map for 1973.

C-9. General collapse of an outbreak is fully dependent on the development of host tree mortality.

Past outbreaks have suffered major setbacks by late spring snowstorms, at the time of year when controlling forces such as parasitoids would be little affected. This kind of event occurred north and east of Chapleau in late May, 1973 when snowstorms and freezing temperatures destroyed virtually all the new shoots of balsam fir and directly or indirectly eliminated a large proportion of spruce budworm populations. A reduction of infestation resulted as shown by the defoliation maps for 1972, Figure 14, compared to 1973, Figure 15. Biologically the expected result would be a major shift of numerical advantage in favour of parasitoids over hosts with accompanying collapse of populations. Yet, infestation intensities rebounded rapidly over the subsequent 2 years and the outbreak continued almost unabated as shown in Figure 16.

Historically the single circumstances under which outbreaks have begun a general collapse in



Figure 16. Infestation map for 1975.

vulnerable forest is the occurrence of extensive and continuous balsam fir mortality. The extent of mortality associated with three collapses as depicted in Figure 13 ranged from 400,000 ha (1 million acres) in 1948 through 640,000 ha (1.6 million acres) in 1976 (Howse et al. 1977) to 1 million ha (2.5 million acres) in 1956.

0. Small remnants of infestation persist following outbreak collapse.

Infestation subsequently occurs within the general area as an outbreak has collapsed. The condition tends to shift location from year to year, disappearing in one area and reappearing in another. Other small areas of infestation may occur in stands at much the same intensity for many years. The area east of Sault Ste. Marie where a major outbreak collapsed in the late 1900s is used to illustrate this point. Here heavy infestation was discovered in 1966 in the upper crowns of mature balsam fir trees in one stand southeast of Sudbury. This infestation was reported only in 1 year. Another infestation in Kinross Twp. near Thessalon persisted at low levels for at least 10 years, 1959-68, with little change in intensity year after year.

These small lingering infestations appear to have an important role in outbreak eruption. Upon discovery, some of them show clear-cut evidence of tree mortality somewhere within their boundaries. The presence of tree mortality in a newly discovered infestation signifies previously undetected and unrecorded defoliation. The reality these small pockets of tree mortality could be overlooked in the flurry of concern over the development of new infestation. Furthermore, they could be misconstrued by those unaware of mapping programs to represent survey omissions on a part of field staff. However, it must be recognized that intensive aerial mapping during outbreak periods when numbers are very low has not been considered (a) until now largely unnecessary and (b) ineffective for the specific purpose of detecting small infestations.

The role of small persistent infestations occurring during periods of endemism has not been studied in depth. However biologically these infestations represent a natural state from which dispersing adults could be expected to emigrate on a regular basis.

Summary of Ten General Characteristics of Spruce Budworm Infestation in Ontario

1. Over the long term, the extent of infestation fluctuates to the extremes.

2. Infestation is present every year somewhere in Ontario or in adjacent provinces or states.

3. Between major outbreaks, numbers generally vary inversely with distance from infestation.

4. Forests show a degree of natural resistance to low levels of moth invasion.

5. New infestations appear to be the result of moth influx from active infestation.

6. Infestation, once initiated tends to spread and give rise to new infestation in the direction of the prevailing winds.

C-7. Infestations that develop in forest types of low vulnerability tend to be short-lived.

C-8. The intensity of infestation once initiated is governed by stand character and climate.

C-9. General collapse of an outbreak is fully dependent on the development of host tree mortality.

C-10. Remnants of infestation persist following outbreak collapse.

Discussion

Greenbank, Schaefer and Rainey (1980) determined through the use of canopy observations, radar and specially equipped aircraft in New Brunswick that moths, including a proportion of females with up to half of their complement of eggs regularly make vertical exits from infested stands during evening hours usually between about 1930 and 2130 hours, under a fairly broad range of conditions. They subsequently orient their flight downwind and displacement distances of upwards of 450 km (280 mi.) were considered feasible over 7-9 hours of flying.

Potential for the spread of infestations is being further elucidated by Dobesberger, Lim and Raske (In press) who describe the premature appearance in July, 1982 of moths in central Newfoundland before local moths had begun to emerge and who provide evidence that these moths originated from mainland New Brunswick.

These new concepts emanating from research provide a scientific basis for interpreting numerous observations made over past decades relating to patterns of infestation. Whereas previously most of the 10 characteristics described could not have been explained without speculation, now new hypotheses can be structured.

Proceeding from the more obvious and distinct to the less apparent and interrelated of the characteristics, new hypotheses are herewith offered. C-6 concerning the shift of infestation, in the direction of prevailing winds, though widely recognized and described over many years, had remained largely unexplained. The hypothesis can now be readily developed that moth dispersal governed by accompanying wind directions greatly influence infestation dynamics particularly in relation to the speed and direction of spread.

Likewise concerning C-7 relative to short-lived infestations in stands of low vulnerability, new insight leads naturally to the hypothesis that infestation of this kind is the direct result of moth influx from active infestations elsewhere.

In the general collapse of outbreaks (C-9) it can be postulated that proportions of egg populations may be wasted when moths disperse into extensive areas of continuous host tree mortal-

ity, an event that would further debilitate already declining populations and contribute to outbreak demise.

Several other characteristics (C-2, C-3 and C-10) when viewed in the perspective of long-range dispersal, provide a backdrop for formulating many new and exciting hypotheses on the biological mechanisms involved. Similarly, characteristics C-4 and C-5, concerning the response of the forest to low levels of influx and to the initiation of new infestation, also broaden the background upon which new hypotheses can be advanced.

To illustrate, it may be postulated that numbers of moths emigrating from a persistent heavy infestation of limited size would disperse in a variety of directions. The result would be an influx of small numbers over a large area. Owing to the natural resistance of stands affected, C-4, the result might be expected to be negligible. However, according to C-9 the original infestation could be expected to persist and eventually through single or repeated chance dispersals, moths will become concentrated, at which time new infestation could develop.

Unfortunately improved new hypotheses taking into account our new appreciation of moth dispersal have been slow to develop. Hopefully the above set of general infestation characteristics will assist. However, additional information is urgently required concerning the precise conditions under which moth dispersal occurs, and does not occur, as well as details of dispersal occurrences and their implications in terms of infestation dynamics on a broad scale.

Collectively the various new hypotheses emerging from infestation characteristics C-1 to C-10 lead me to a general control strategy, which if applied offensively could conceivably have major implications in managing future outbreaks.

Proposal

Characteristics of infestation based on 37 years of intensive surveys combined with recent findings on moth dispersal reveal a logical long-term outbreak control strategy that aims simply at the removal of source infestation. The concept has been developed that in the absence of infestation a widespread outbreak might not develop. The key question is: Could the next outbreak be avoided in Ontario if during a period of history when the extent of infestation was extremely low, all infestations including those in adjoining areas within the range of moth dispersal were eliminated or retained at levels below which moth dispersal would occur? A more general and futuristic version of the same question might be: could the next outbreak be avoided in North America? Recognizing existing circumstances in which some jurisdictions are applying a 50+ year projection to an assumed continuous infestation (Baskerville 1983) it is unrealistic to contemplate the elimination of infestation throughout the range of spruce budworm at this time. However, it might be appropriate to consider outbreak prevention for

the western sector of its range over the next 10 years. This would require detailed and coordinated monitoring including the detection and evaluation of all infestations over a large area crossing the International Border, followed by international action against centers that constitute a source of dispersal.

A major limitation in such a suggestion is the narrow window in the extensive time frame through which man could effectively influence infestation development, namely, subsequent to the decline of one outbreak and before the start of another.

Beyond the enormous economic advantage success would have, the concept also offers the challenge of applying integrated control methods over limited forest areas. It is unlikely that any intense infestation discovered on either side of the International Border could be allowed to develop unimpeded while the forces of integrated control took hold. However, abatement treatment begun immediately could be followed by integrated methods to reduce populations further. The concept offers alternative strategies for forest management on a grand scale and provides for management action commensurate with historical reality.

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CANUSA WORKSHOP

NEW & IMPROVED TECHNIQUES FOR MONITORING AND EVALUATING SPRUCE BUDWORMS

Burlington, Vermont
September 13-15, 1983

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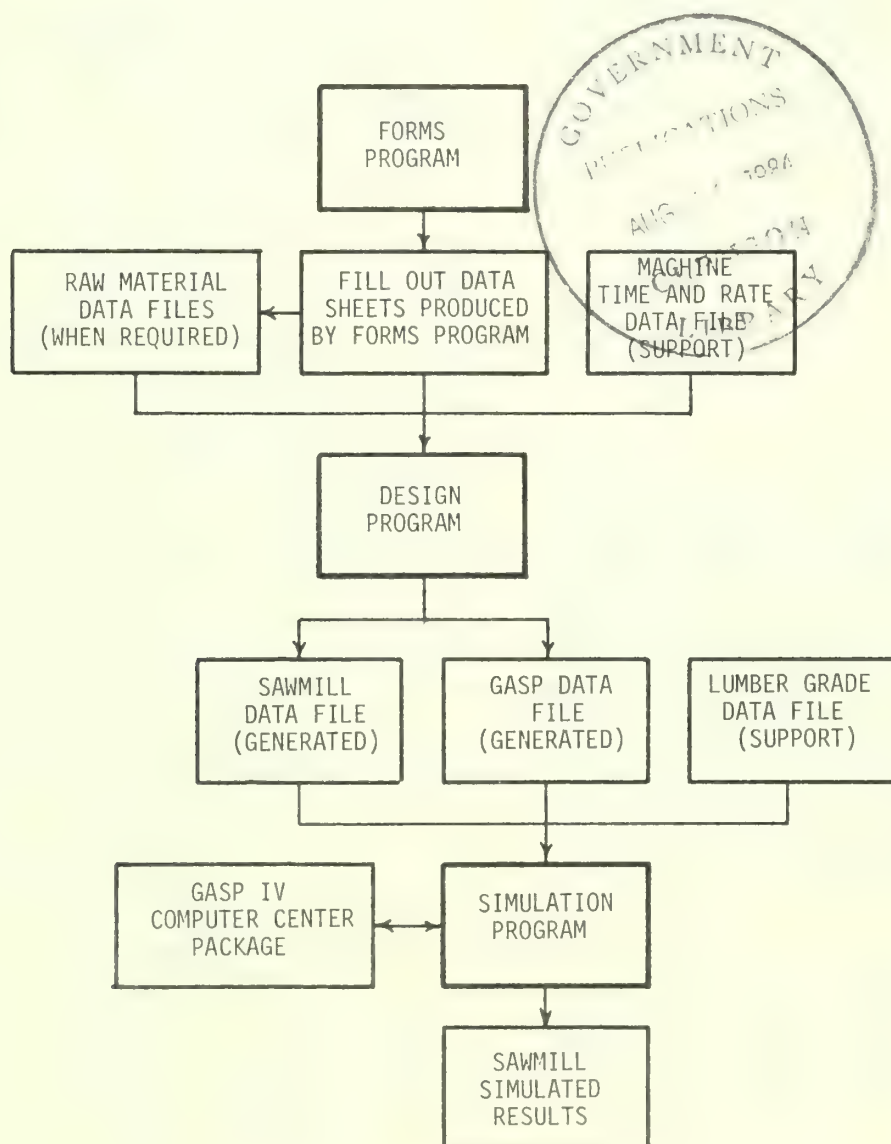
Presents new or improved methods available for monitoring and evaluating spruce budworm populations.

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DESIM: A System for Designing and Simulating Hardwood Sawmill Systems

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Abstract

DESIM is a comprehensive tool for designing and simulating hardwood sawmill systems. Developed to handle complex sawmill designs and many possible raw material/product mixes, it provides a valuable analytical tool for sawmill managers and designers. It is a user-oriented system that makes it easy to change many factors including the design itself to analyze the operation of new or modified mills before they are built.

Introduction

Sawmill analysts have found that many hardwood mills in the Northeast are not set up to process available raw materials efficiently. The problem has been compounded by changing market conditions that have forced mills to produce products other than those they were originally designed for. New mills must be built and existing mills modified to handle the changing raw material and product mixes efficiently. A new system called DESIM¹ (DEsign SIMulator) can help in the design of new mills and the modification of existing mills to achieve this efficiency.

DESIM is the only system of its kind available for designing and simulating hardwood sawmill systems, a valuable analytical tool for sawmill managers and designers. With the present high costs of construction and equipment, new or modified mills must do the job for which they are built. Even minor modifications are costly afterward. DESIM allows a thorough look at the operation of a mill before it is built or modified, providing answers to important questions such as:

- Are the conveyor and surge deck systems adequate?
- Are there any bottlenecks?
- What happens if raw material size and/or grade distributions change?
- What happens if the product mix changes?
- How will an increase in downtime affect production?
- How will adding a piece of equipment affect production?

This is a user-oriented system that makes it easy to test the effect of changes in many factors, including the design itself, on answers to these and many other questions.

¹The computer programs described in this publication are available on request with the understanding that the U.S. Department of Agriculture cannot assure their accuracy, completeness, reliability, or suitability for any other purpose than that reported. The recipient may not assert any proprietary rights thereto nor represent them to anyone as other than Government-produced computer programs.

Because DESIM was developed to handle complex sawmill designs and many possible raw material/product mixes, it requires a large mainframe computer such as those available at most universities. An IBM 370/158² was used to develop and test it. And, because the system uses the GASP IV FORTRAN-based simulation language, users must have the GASP IV package available (Pritsker 1974, 1977). A conversational monitor system (CMS) computer terminal is also required to handle the question and answer technique used to set up and/or change mill designs. To many potential users, these requirements may seem unreasonable, however, with a CMS computer terminal and a telephone hookup (modem), adequate computer facilities are only a telephone call away.

Although the system requires the use of a large computer, it is relatively inexpensive to use. The cost will depend on (1) the size and complexity of the mill being designed; (2) the length of operating time being simulated; and (3) the various changes required by the computer center. However, it should not cost more than \$25 to set up a design and simulate an 8-hour operating shift for a complex mill with a large raw material/product mix.

The following discussion is divided into three parts: (1) the DESIM system, (2) the required inputs, and (3) the resulting output. This paper will give the reader a general understanding of the system; greater detail can be found in the DESIM user's manual.³

²The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture or the Forest Service of any product or service to the exclusion of others that may be suitable.

³Adams, Edward L. DESIM user's manual. (In preparation for publication, Northeastern Forest Experiment Station, USDA Forest Service, Princeton, WV.)

DESIM System

A great deal of effort has gone into making the DESIM system easy to use. To this end, the system has been divided into the following parts: (1) a FORMS program, (2) a DESIGN program, (3) a SIMULATION program, (4) two support data files, and (5) several generated data files. The two support files include standard machine times and rates for different types of sawmill equipment and lumber grade information (Hanks 1973; Hanks et al. 1980) used to assign lumber grades to the boards produced. The generated files include up to five raw material data files that are supplied by the user if actual log and/or bolt information is used as input. The generated data files also include a sawmill data file and a GASP data file produced by the design program. Figure 1 shows the interaction of these various parts.

To illustrate how the DESIM system works, each program and its relationship to the different data files will now be discussed.

FORMS Program

The FORMS program produces the data sheets necessary to set up an entire milling situation. Of the 22 different types of data sheets available, the user can specify the ones wanted and the quantity of each. This is much more efficient than providing blank forms that must be filed and then copied when needed. The program provides data sheets for: (1) raw material inputs, (2) machine center information, (3) conveyor and surge deck (buffer) systems, (4) material processing instructions, and (5) material routing instructions. A user's manual provides instructions for filling out these data sheets. The systematic approach used in the data sheets and the user's manual reduces the difficulty of setting up a sawmill system, even for a very complex situation. Once the data sheets have been filled out and the raw material data files created (if needed), then the DESIGN program is run.

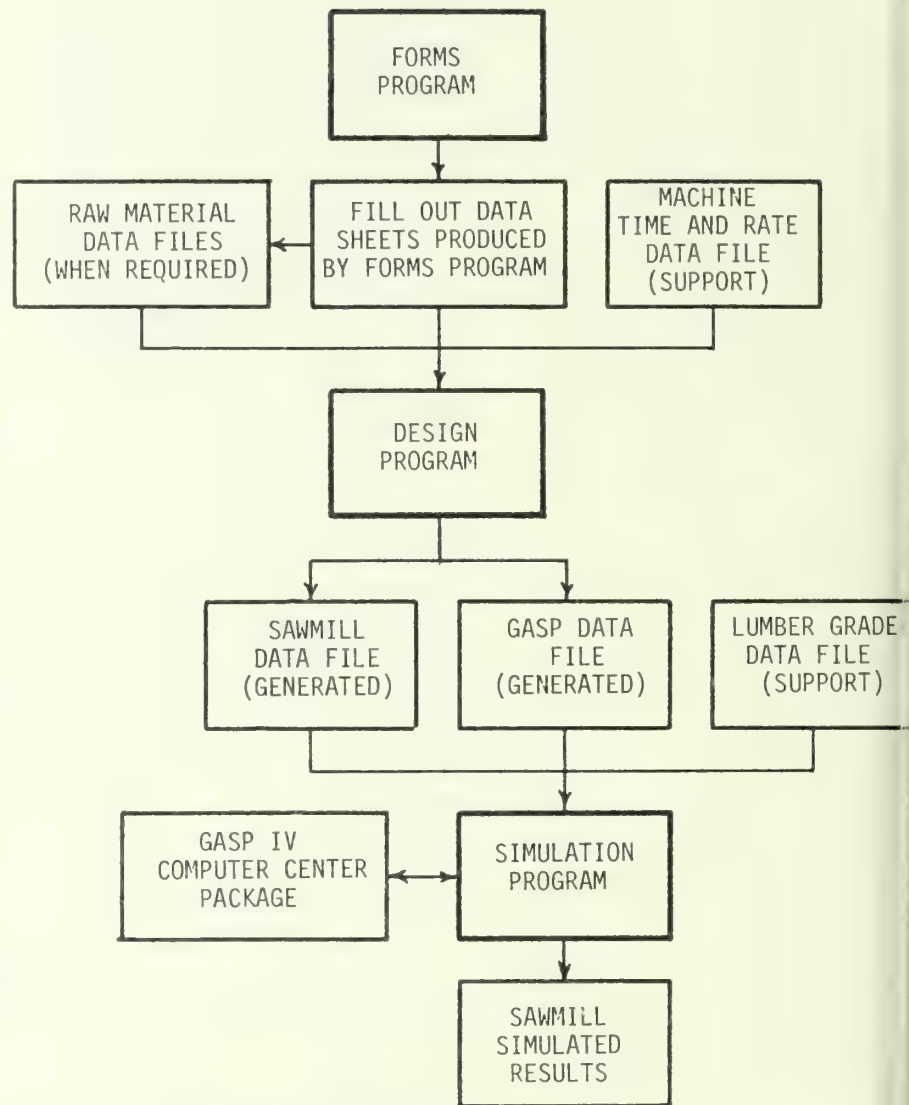


Figure 1.—Flow diagram of DESIM systems.

DESIGN Program

The DESIGN program is used to get the information from: (1) data sheets, (2) machine times and rates data file, and (3) raw material data files, when used, into the form required by the SIMULATION program. DESIGN is an interactive program that asks the user questions and solicits the answers. Most of the answers come directly from the data sheets produced by the FORMS program and filled out by the user. The user is shown the standard values in the machine times and rates file, and asked whether any of them should be changed. If the user answers yes, the system asks for the new values. This question and answer procedure is used both for setting up and for changing a sawmill system. When the user has answered all of the questions, the program produces the sawmill data file and the GASP data file needed by the SIMULATION program. The GASP data file contains the control information needed by the GASP V simulation package.

SIMULATION Program

Finally, the SIMULATION program is used to simulate the actual operation of the proposed sawmill system. Inputs to the program include: (1) the sawmill data file, (2) the GASP data file, and (3) the lumber grade data file. Using this information, the logs and/or bolts are "processed" into the various

end products at the specified processing times and rates. The individual pieces are routed from machine center to machine center according to the lengths and speeds of the conveyors and buffers involved, and the machine is shut down as in the specified downtime information. In this way the simulated run reflects the material slacks, surges, and back-ups that would occur in the actual mill operation, and provides estimates of the busy, idle, blocked, down, and purge times that might be expected for different machine centers. Purge time as used here is that nonproductive time caused when the headrig is shut down early to allow material to clear the mill system by the end of the shift.

If, after evaluating the output for the simulated operation of a proposed sawmill system, the user wishes to change any aspect of it, it is only necessary to rerun the DESIGN program. The program will ask questions and prompt the answers needed to make the changes. Once the changes are made, the DESIGN program provides a new sawmill data file. This new data file is then processed by the SIMULATION program to provide a new set of results. This makes it possible for the user to try many different situations in the search for the best mill for a given raw material/product mix.

Required Inputs

As mentioned in the previous section, the required DESIM inputs include: (1) raw material information, (2) machine center information, (3) conveyor and buffer information, (4) material processing instructions, and (5) material routing instructions. In this section, the inputs will be discussed in greater detail.

Raw Material Information

The raw material inputs can be in the form of actual piece data, log size frequency distributions, and/or bolt size frequency distributions. Up to five separate sets of data can be used in each of these categories. The allowable species include northern red oak, black oak, scarlet oak, white oak, chestnut oak, yellow-poplar, hard maple, soft maple, basswood, black cherry, beech, and yellow birch. Other species can be used, but that would require minor modifications to both the DESIGN program and the SIMULATION program. It would also require changing the lumber grade information in the lumber grade data file.

The actual piece data include information such as piece number, species code, top diameter, butt diameter, and length. If the piece is a sawlog, the standard USDA Forest Service hardwood factory-lumber log grade is included. However, if the log

Machine Centers Information

is of subfactory class, Grade 4 is used. And, because there are no standard bolt grades, Grade 5 is used for all bolts. When the logs and/or bolts represent pieces to be processed from long-length material, a piece position code is also included in the data. The five data sets allowed in this input can be any or all of the following types:

- Long-length material to be bucked into sawlogs
- Long-length material to be bucked into bolts
- Long-length material to be bucked into both sawlogs and bolts
- Individual standard sawlogs
- Individual bolts

The sawlog frequency distribution data will accept a species frequency distribution (in percent) for up to five species in each of five data sets. For each species, it will accept a grade frequency distribution (in percent) for up to four log grades. Grades 1 through 3 are the standard USDA Forest Service log grades and Grade 4 is for subfactory-class logs. For each log grade included in the data, log-size frequency distributions (in percent) are required for both diameter classes and length classes.

The bolt frequency distribution data are the same as those for sawlogs, but bolt-grade frequency distributions are not used. Each of the five data sets will accept a species frequency distribution for up to five species. For each species included in a set, bolt size frequency distributions are required for both diameter classes and length classes.

DESIM allows the user to work with sawmill systems having up to 29 machine centers, including up to five headrigs. Within these constraints the system can have any combination of the following machine centers:

- Raw material handler (forklift and crane)
- Bucksaw
- Debarker (all kinds)
- Headrig (circular, band, Scragg, and gang)
- Headrig w/vertical edger (circular and band)
- Edger (standard and combination)
- Resaw (gang, centerline, and line-bar)
- Special products station
- Trimsaw
- Greenchain
- Chipper
- Transfer station (cross transfer chain from conveyor to conveyor)

The special product station listed above can be used to simulate any process that produces products by cutting boards or cants into shorter pieces, such as half-headers used in coal mines.

For each of the above machines used in a design, the appropriate time and/or rate information is required. This information includes:

- Material loading time
- Material turning time
- Material processing time or rate
- Machine downtime

Depending on the machine, these times are represented by lognormal frequency distributions, time per surface area, or fixed time. Processing rates are in feet or inches per minute. The machine time and rate data file has this information for many of the machines. However, if this information is not available in the data file for a given machine, or the user does not wish to use the available information, the user must provide it. The user's manual gives the necessary instructions.

Conveyor and Buffer Information

DESIM can handle almost any conveyor and buffer layout the user might want. A buffer, as mentioned earlier, is a surge deck used to store material just ahead of a machine center. Each buffer can receive material from any number of conveyors and/or machine centers. Up to four buffers can feed a given machine center. Each conveyor can receive material from any number of machine centers. Material can be cross transferred from one conveyor to another. And, a merry-go-round conveyor-buffer system can return material for multiple passes through a given machine center.

Material Processing Information

To simulate the sawing of logs and bolts, DESIM uses a sawing subroutine, a modified version of a computer program developed by Airth and Calvert (1973). This subroutine makes a wide variety of different sawing patterns available to the user. Besides allowing for live sawing on a gang headrig, it allows the following sawing patterns to be simulated: circular, band, and Scragg headrigs.

ircular and band headrigs:

Live saw
Saw around (all)
Saw around to timber
Saw around to cant for resaw
Saw around to 2-sided cant for resaw
Saw around to 3-sided cant for resaw
Slab around to timber (slabs to resaw)
Slab around to timber (slabs to chipper)
Slab around to cant for resaw (slabs to resaw)
Slab around to cant for resaw (slabs to chipper)
Slab around to 2-sided cant for resaw (slabs to resaw)
Slab around to 2-sided cant for resaw (slabs to chipper)
Slab around to 3-sided cant for resaw (slabs to resaw)
Slab around to 3-sided cant for resaw (slabs to chipper)

cragg headrig:

Saw timber (slabs to resaw)
Saw timber (slabs to chipper)
Saw cant for resaw (slabs to resaw)
Saw cant for resaw (slabs to chipper)
Saw 2-sided cant for resaw (slabs to resaw)
Saw 2-sided cant for resaw (slabs to chipper)

For each of these sawing patterns that will be used, the designer must enter such information as: (1) minimum allowable board length, (2) required saw kerfs, (3) rough board thicknesses, (4) nominal board thicknesses, (5) allowable board widths, (6) allowable cant or timber thicknesses, and (7) allowable cant or timber width.

Up to 100 sawing patterns can be specified for each headrig in the sawmill system. The simulator selects the proper sawing pattern for a given sawlog or bolt based on controls set up by the user. These controls are based on raw material species, grade, and size. Also, within a given species, grade, and size of raw material, the controls can select a sawing pattern on a sequential basis or a percentage basis. For example, three different sawing patterns can be set up for Grade 3 red oak logs greater than 16 inches in diameter. If a sequential basis is used, the simulator selects the first sawing pattern, then the second, then the third, and then back to the first as logs meeting the stated criteria are to be processed. If a percentage basis is used, the sawing patterns are based on the percentages entered by the user. There is enough flexibility in these instructions to allow for realistic simulation of many different processing procedures.

Material Routing Information

DESIM allows complex routing of material through the simulated sawmill system. The routing is controlled by criteria entered by the user during the design phase. These criteria include such factors as material type, species, grade, width (or diameter), thickness, and length. Material meeting given criteria can also be sent to one of as many as three separate machine centers on a: (1) priority basis, (2) sequential basis, or (3) percentage basis. An example of routing on a priority basis would be a 6- by 8-inch red oak cant sent to a gang resaw except when the resaw is down or its buffer is full. Then the cant is sent to the next designated machine center. Routing on a sequential or percentage basis would be similar to the process discussed above for picking sawing patterns.

This routing procedure allows for realistic passing of material from machine center to machine center. It also allows DESIM to simulate the decisions made in actual sawmill operations when material surges and blockages affect the flow of material through the system.

Resulting Output

If the input information accurately reflects the characteristics of an existing or proposed system, DESIM should realistically simulate its operation. In other words, the output will indicate what can be expected from the sawmill when it is processing given raw materials into specified products. There is enough information in this output to tell how well a new or modified mill can be expected to perform. Given the ease and relatively low cost of obtaining this output for different mill designs, the user can thoroughly investigate a wide range of possibilities before selecting the best one for a given situation.

The DESIM output can be divided into three categories: (1) raw material summary, (2) machine statistics, and (3) product yield summary. The following discussion provides a more detailed look at these outputs.

Raw Material Summary

For sawlogs processed through the design mill, this summary shows the percentage of each species. Within a species, it shows the percentages by log grade. And within

each log grade, it shows the frequency distributions by both diameter and length classes. The summary is the same for bolts, but bolts are not graded. Table 1 shows an example of this summary for hard maple sawlogs.

This output serves two purposes: First, it allows the user to determine that the raw material processed during the simulation run reflects the raw material information entered as input; and second, when kept with the other results, it provides a record of the raw material used to obtain those results.

Machine Statistics

For each machine center used in the design, this output provides:

- Productivity in Mbf (thousand board feet) per hour, Mft³ (thousand cubic feet) per hour, or tons per hour
- Products, by type, showing number of pieces and volume
- Busy, blocked, idle, down, and purge time by number of occurrences, amount, and percentage of total operating time
- Conveyor and buffer utilization by length and percent

Table 1.—An example of raw material input summary

Log Information

Percent Hard Maple = 100.0

Percent Grade 1 = 17.6		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Diameter		0	0	0	0	0	0	0	0	0	0	3	4	2	2	3	1	1	0	1	2	0
Logs		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.5	16.7	8.3	8.3	12.5	4.2	4.2	0.0	4.2	8.3	0.0
Percent																						
Length		8	9	10	11	12	13	14	15	16												
Logs		3	0	6	0	6	0	6	0	3												
Percent		12.5	0.0	25.0	0.0	25.0	0.0	25.0	0.0	12.5												
Percent Grade 2 = 37.5		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Diameter		0	0	0	0	0	0	3	6	12	6	10	3	4	3	1	2	1	0	0	0	0
Logs		0.0	0.0	0.0	0.0	0.0	0.0	5.9	11.8	23.5	11.8	19.6	5.9	7.8	5.9	2.0	3.9	2.0	0.0	0.0	0.0	0.0
Percent																						
Length		8	9	10	11	12	13	14	15	16												
Logs		6	0	17	0	11	0	8	0	9												
Percent		11.8	0.0	33.3	0.0	21.6	0.0	15.7	0.0	17.6												
Percent Grade 3 = 44.9		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Diameter		0	0	0	0	4	12	9	11	5	0	5	3	3	1	3	1	0	1	1	0	2
Logs		0.0	0.0	0.0	0.0	6.6	19.7	14.8	18.0	8.2	0.0	8.2	4.9	4.9	1.6	4.9	1.6	0.0	1.6	1.6	0.0	3.3
Percent																						
Length		8	9	10	11	12	13	14	15	16												
Logs		6	0	20	0	12	0	10	0	13												
Percent		9.8	0.0	32.8	0.0	19.7	0.0	16.4	0.0	21.3												

Table 2 shows an example of this output for a circular headsaw. Notice in the example that three different productivity values are given: (1) maximum, (2) no down time, and (3) in this system. The "maximum" productivity shows what could have been expected if the machine had produced during the total operating time. The "no down time" productivity shows what could have been expected if the machine had had its normal blocked, idle, and purge times but no down time during the total operating time. And the "in this system" productivity shows the actual productivity of the machine in the design system. This information not only shows the user how well the machine did in the system, it also indicates the possibility for improving productivity.

Also in the example (Table 2), you will notice a zero length and zero utilization for the conveyor. This shows that there was no conveyor between the headrig and the machine center sending logs to the headrig. In other words, that machine was sending the logs directly to the buffer.

Product Yield Summary

This output provides product yield tables related back to the primary breakdown machines. Each table provides the following information by log or bolt diameter class:

- Number of logs or bolts processed
- Scale volume (International 1/4-inch)
- Tally volume
- Percent overrun
- Cubic volume
- Lumber recovery factor
- Percent yields by lumber grades, special products, and timbers

Table 2.—An example of machine statistics for a circular headsaw
Equipment Information

Equipment No. 4 (Circular Headsaw)

Productivity:

1.38 M bf/hour (maximum)
1.29 M bf/hour (no down time)
1.27 M bf/hour (in this system)

Products:

Number of pieces:

Lumber 1,194
Slabs 432
Total 1,626

Volume:

Lumber 10,184 bf

Time:

	Number	Minutes	Percent
Busy	1,518	443.19	92
Blocked	0	0.0	0
Idle	1	1.99	0
Down	15	29.00	6
Purge	1	5.81	1
Total		480.00	100

Conveyor utilization:

	Type code	Length (ft)	Utilized (ft) (%)	
Conveyor (3, 4)	1	0.0	0.0	0.0

Buffer utilization:

	Type code	Length (ft)	Utilized (ft) (%)	
Buffer (3, 4)	1	20.0	21.6	108.0

For each primary breakdown machine, yield tables are presented by species, log grades, and bolts. A yield table is also presented for each primary breakdown machine with all species, log grades, and bolts combined. And finally, a summary yield table is presented for all logs and bolts processed through all primary breakdown machines. Table 3 shows an example of a yield table for Grade 1 hard maple sawlogs processed on a circular headsaw.

The product yields were shown in this manner to allow the user to check them against published yields. In this way the user can be assured that the simulated results are within reason. In designing a new mill or making modification of an existing mill, this comparison will make it easier to show that the simulated results for the mill are realistic.

Table 3.—An example of the product yield summary for a circular headsaw

Yield Information													
Species = Hard Maple; Grade = 3													
Primary Breakdown Unit No. 1 (Circular Headsaw)													
Diameter	Number logs	Scale volume	Tally volume	Overrun	Cubic volume	LRF	FAS	SEL	Lumber 1C	2C	3C	Special products	Timbers
8	4	120	113	-5.83	22	5.05	0.0	0.0	6.19	1.77	92.04	0.0	0.0
9	11	385	353	-8.31	67	5.29	0.0	0.0	3.40	5.95	90.65	0.0	0.0
10	7	355	349	-1.69	59	5.89	0.0	2.58	15.76	9.74	71.92	0.0	0.0
11	9	560	559	-0.18	89	6.25	0.0	0.0	16.64	22.90	60.47	0.0	0.0
12	3	170	163	-4.12	26	6.22	0.0	0.0	3.07	43.56	53.37	0.0	0.0
14	3	350	347	-0.86	51	6.79	0.0	0.0	9.51	51.87	38.62	0.0	0.0
15	3	305	286	-6.23	43	6.66	0.0	1.40	16.08	31.12	51.40	0.0	0.0
16	2	220	214	-2.73	30	7.09	0.0	2.80	20.09	49.53	27.57	0.0	0.0
18	2	340	239	-29.71	46	5.17	3.77	6.28	33.05	43.10	13.81	0.0	0.0
19	1	260	248	-4.62	35	7.09	6.85	8.47	24.19	12.50	47.98	0.0	0.0
21	1	195	182	-6.67	26	7.13	0.0	9.89	18.68	21.43	50.00	0.0	0.0
22	1	260	249	-4.23	34	7.34	5.62	0.0	15.26	49.40	29.72	0.0	0.0
24	2	680	654	-3.82	87	7.48	2.75	2.60	22.63	34.56	37.46	0.0	0.0
Total	49	4,200	3,956	-5.81	615	6.42	1.47	2.28	16.51	29.15	50.61	0.0	0.0

Discussion

The best hardwood sawmill for a given location must be determined by the available raw materials and product markets. However, in this age of rapid changes, a manager may wish to build or modify a mill to handle a wider range of raw material and product mixes more efficiently. This makes designing or planning the modifications of a mill much more difficult. The DESIM system can be a valuable tool in this process.

DESIM can handle large complex sawmill situations. The many sawing decisions made by head sawyers can be simulated. And the material processing and routing decisions made by the other machine operators to produce and route a wide variety of different products are no problem for the system. In other words, the DESIM system can be used to design and simulate the operation of almost any hardwood sawmilling situation the user wishes to consider.

Although the system is complex, the procedure used to set up and simulate the operation of a sawmilling situation is relatively simple. This procedure also makes it easy to change the sawmilling situation and obtain new simulated results. Therefore, at a relatively low cost and with little time and effort, the user can look at many different situations and pick the sawmill design that best fits a given range of raw material/product mix situations. This not only guarantees an efficient mill for the money, but reduces the possibility that costly modifications will be needed in the future.

Copies of the program may be obtained from the Forestry Sciences Laboratory, Northeastern Forest Experiment Station, P.O. Box 152, Princeton, WV 24740.

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DESIM is a new system for designing and simulating the operation of hardwood sawmill systems. Sections are presented on: (1) the system, (2) required inputs, and (3) resulting outputs. This computer system is relatively easy to use for even a very complex sawmilling situation.

ODC 832.11

Keywords: Computer program; management, operations research

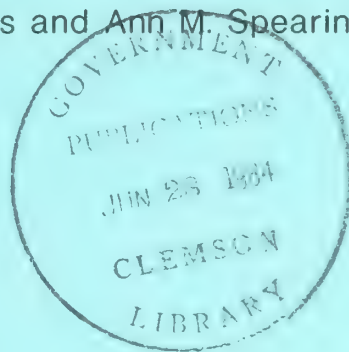
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-

Research in Forest Productivity, Use, and Pest Control

Proceedings of a symposium held at the
University of Vermont, Burlington,
September 16-17, 1983, in recognition
of the contributions by women scientists.

Edited by Margaret M. Harris and Ann M. Spearing



ABSTRACT

Proceedings of a symposium sponsored by the Civil Rights Action Committee of the Northeastern Forest Experiment Station and the University of Vermont School of Natural Resources to provide a forum for the presentation of current research in natural resource fields by women scientists.

Each contributor is responsible for the accuracy and style of her paper. Statements of the contributors from outside the U.S. Department of Agriculture may not necessarily reflect the policy of the Department. The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture or the Forest Service of any product or service to the exclusion of others that may be suitable.

RESEARCH IN FOREST PRODUCTIVITY, USE,
AND PEST CONTROL

Proceedings of a symposium held at the University of Vermont, Burlington,
September 16-17, 1983, in recognition of contributions by women scientists.

Sponsored by
USDA Forest Service, Northeastern Forest Experiment Station,
University of Vermont, School of Natural Resources

Edited by

Margaret M. Harris

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FOREWORD

In 1982 the Northeastern Forest Experiment Station and the Northeastern Area State and Private Forestry set aside a portion of their Civil Rights budget to fund a number of special projects. It had been a high priority goal of the Forest Service to promote, enhance, and endorse Civil Rights activities, and the Special Project Fund was an innovative addition to the existing Civil Rights Affirmative Action Plan.

On September 24, 1982, the staff of the Burlington Laboratory of the Northeastern Forest Experiment Station responded to the call for special project proposals and submitted, in cooperation with the faculty of the School of Natural Resources of the University of Vermont, a request to support a seminar for women natural-resource professionals. Although there are more women in forestry than ever before, the numbers of women who are principal researchers, forestry professors, and forest managers are still small compared to the numbers of men in these jobs. Furthermore, because they have entered forestry in significant numbers only recently, women forest researchers have not been highly visible. Therefore, a proposal was drafted to organize a symposium which would serve as a forum for women foresters to share their work and set up professional communications among women in the various forestry agencies. It was further intended to provide an outlet for recent research findings.

Admittedly, the ratio of women to men in forestry is small, but when we began our search for qualified women researchers, we found many candidates in federal, state and private employment. It was difficult to choose among very capable and highly recommended professors.

The final agenda covered a full day and included with a mix of formal presentations, panel discussions, and audience questions. It is our intention, in publishing these proceedings, to make available to the public the research work of the women natural-resource scientists in the United States. Perhaps this publication will serve to attract others to any future symposiums of this kind and encourage the interest of students in environmental curricula.

The program committee thanks the many people who contributed their time and efforts to the success of the symposium. Particular thanks go to M. J. Moore at the University of Vermont School of Natural Resources and Elizabeth Crosby, U.S. Forest Service, Burlington, for editorial and secretarial assistance to the personnel from the U.S. Forest Service in Washington, D.C., for their support of our endeavors. Finally, we wish to thank all speakers, panel members, and guests who made the symposium happen.

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PREDICTING RESPONSE OF
FOREST DEFOLIATORS TO INSECTICIDES¹

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Abstract.--This report describes an approach we are using to understand differences in response of forest insects to control efforts with insecticides. Why, for example, does spraying kill some insects but not others? Why does a certain chemical work sometimes but not other times? To help answer these questions, we are integrating results of basic research on insect biology, toxicology, ecology, and genetics. A computer model has been developed that incorporates information on extrinsic variables (chemical, dose, rainfall) and features of the insects themselves (species, developmental stage, genetic level of susceptibility). Using this model, cumulative effects of key variables can be simulated and predictions of population response made. We have found, for example, that for the Douglas-fir tussock moth, timing of spray application is crucial when acephate is used. For carbaryl, it is particularly important to know the genetic makeup of the population to be sprayed. For the western spruce budworm, timing of spray is not as critical as dose. This model is permitting more accurate forecasts of insecticide efficacy and will enable forest managers to use chemical control more judiciously.

INTRODUCTION

Biological systems are enormously complex. To deal with them effectively, as scientists and as human beings, we must first simplify them, trying to understand one small part at a time, then putting these pieces of knowledge together, bit by bit, to build a solid edifice of understanding. At the same time, we must continually seek ways to view our ideas and our perceived understanding in new ways, from different perspectives. We must continually rearrange our knowledge, as we add to it, so that it more closely approximates reality. Ultimately, what we seek is to be able to predict, to take our understanding of a limited

area of the universe and to extrapolate accurately to other areas of the universe.

The history of forest entomology and approaches used to study forest insects today reflect all of these aims. Forest entomologists began, about 100 years ago, by describing and categorizing the insects they discovered. Little consideration was given to their relationships to the forest and to each other. However, as the necessity for more intensive management of forests resulted in the practical science of forestry, so has forest entomology become more practical in orientation. Other factors have also influenced the development of modern approaches in forest entomology and have opened up new areas of study. Important discoveries, such as that of chemical communication, and technical advances, such as computer-aided data processing, have revolutionized the ways that we study insects and the perspectives with which we view them. Perhaps most significant has been the evolution of integrated approaches to problem-solving. Interdisciplinary research efforts are now more the rule than the exception; we work less and less productively in isolation from each other. There is also a much greater awareness of interactions among the various facets of the ecosystem.

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Yet many of the questions that forest managers and forest scientists are asking today are very similar to the questions that have been asked for the past several decades. For example, why do outbreaks of forest insects occur in some places and not others? What starts an outbreak and what causes the natural decline in numbers at the end of an outbreak? Why does spraying kill some insects but not others? Why does a certain chemical work sometimes but not other times?

In spite of the importance of these questions, and the extraordinary amount of time, effort, and money that has gone into answering them, not much progress has been made. Part of the problem lies in the great complexity of the system we are trying to understand. To simplify our understanding of the interactions between insects and their environment, Clark et al. (1967) developed the life system concept (Fig. 1). According to this scheme, an organism's success, measured by its numbers and persistence, results from the interaction of the genetic makeup of its component individuals with the effective environment.

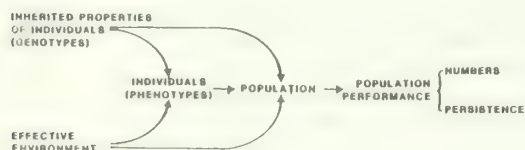


Figure 1.--The life system, showing the relationship between genotype and environment.

Conceptually, the life system is very satisfying; in practice, it is not particularly easy to work out which, of all the variables, constitute the "effective environment" or how to characterize the genetic makeup of the population. But this scheme has helped show us that some of the problems we have had in acquiring answers to our questions may arise from a focus on the environmental aspects of the system, at the expense of an understanding of the genetic or intrinsic components of insect populations. As Wellington (1977) pointed out,

For decades, a "population" has been viewed as a passive, monolithic lump of protoplasm, out of which chunks are carved by all the lethal agents assailing it. The comparative . . . practical values of any agent have been judged primarily by the size of the chunk it removes That preoccupation has prevented us from recalling that the pests which con-

cern us most have been surviving in very hostile environments much longer than we have been trying to destroy them.

We are asking, How can we kill more of them?, when we should be asking more relevant questions, such as, What adaptations allow them to evade extinction? And we have paid for our resulting ignorance every time a conventional pest control program has failed.

Because it is being recognized that our view of insect control is rather one-sided, there has been an increasing attention to the attributes that promote species survival, on population variation--the "other half" of the life system. In our research, we set out to understand relationships between genetic and toxicological variation among forest insect populations. Our work focused on two of the questions posed above: Why do insecticides kill some insects and not others, and why are chemicals effective sometimes but not other times? Our aim has been to develop a realistic scheme for accurately predicting results of insecticide application in field situations.

From the toxicological perspective, laboratory experiments--because they are less expensive and inherently more controlled than field trials--have traditionally been used to estimate results of field application of insecticides. Early laboratory studies emphasized testing of chemicals by directly applying them to fully exposed insects, then extrapolating results to suggest field application rates. This procedure is inherently inaccurate because measurement units in topical application bear little, if any, relationship to those actually reaching insects in the field. Factors such as shielding of insects by foliage, dilution of chemicals by rainfall, differential response within and among populations, and ingestion of the chemical by feeding on sprayed foliage must also be considered. Over time, laboratory bioassays have become increasingly sophisticated, incorporating evaluation of the effects of all these variables. At the Berkeley USDA Forest Service laboratory, a comprehensive data base on the toxicological response of two important forest defoliators--the Douglas-fir tussock moth (*Orgyia pseudotsugata* McDunnough) and the western spruce budworm (*Choristoneura occidentalis* Freeman) has been systematically accumulated over the past 15 years.

It is now clear, from these and related studies, that genetic variation in population response should be considered when chemical control is used. In these two species, we found not only differences in tolerance (a general term used to describe the natural variation in response occurring among populations of a species) but also apparent resist-

ance (a term conventionally used to describe the response of insect strains actually modified by insecticide usage). Tests on Douglas-fir tussock moth populations revealed a two-fold difference in response to carbaryl (expressed as ratios of LD_{50} s) when just four populations were examined (Stock and Robertson 1979). To determine whether these differences had an underlying genetic basis, we tested sibling groups (offspring from single-pair matings in the laboratory) and found significant variation among groups (in one case, a 12-fold difference). Similar work with the western spruce budworm revealed a three-fold difference in tolerance to acephate between a field population from Idaho and a laboratory colony (Stock and Robertson 1980). Response of budworm sibling groups also varied nearly three-fold. More recent studies (see Robertson and Stock, these proceedings) have shown that some western spruce budworm populations are 18 times more tolerant of carbaryl than others.

Further research has been aimed at understanding the specific genetic and physiological mechanisms underlying differential population response. Once an insecticide enters an insect's body, it is subject to degradation by a variety of enzymes. Whether or not death occurs is directly related to the efficiency of key enzymes in the detoxification process. The role of esterases in the hydrolysis of organophosphate toxicants, such as acephate, resulting in formation of nontoxic products, is well known. Insect esterases are highly polymorphic; in some groups, as many as 20 alleles have been observed at one esterase locus. Variation in these enzymes has been linked to variation in response to organophosphates in a number of insect species (e.g., Beranek 1974, Pasteur and Sinegre 1975, Sudderuddin 1973). Commonly present among the esterases are silent (null) alleles which code for inactive enzymes or no proteins and which may also be associated with differences in tolerance among groups. Differential response of at least two insect groups, including the western spruce budworm, has been related to frequencies of null alleles at an esterase locus (Stock and Robertson 1982, Tsakas and Krimbas 1970). Insect esterases have thus provided a rich source of experimental material for the study of insecticide effects.

The technique we used to identify differences in esterases within and among populations is electrophoresis, the separation of charged molecules in an electric field. Proteins produced by different gene forms at a chromosome locus commonly differ slightly in overall charge. Thus, when they are put into an electric field, they will migrate in one direction or other at a speed related, in part, to their charge, and the different gene products will separate out (Fig. 2). In practice, homogenate of individual insects is absorbed onto small

paper wicks and inserted into a starch gel medium. Then an electric current is applied for a few hours and the proteins move through the starch gel medium. Separate slices of the gel are then stained with substrate-specific stains which color those areas of the gel where the different products of a particular gene type have localized. One can then see bands on the gel, a direct visualization of genetic similarities and differences among individuals in a population, and quantitative information is obtained for comparison of groups. Such data are particularly useful for evaluating overall population or species relationships in taxonomic and evolutionary studies, or for comparisons of specific gene types, such as the esterases in toxicological work.

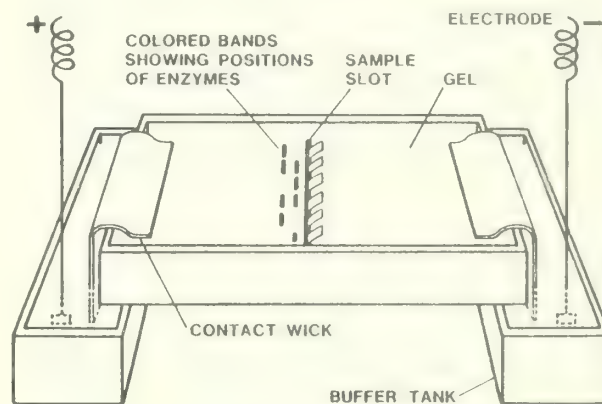


Figure 2--Schematic diagram of the technique of gel electrophoresis.

On the basis of combined genetic and toxicological work of this type, we were able to categorize Douglas-fir tussock moth and western spruce budworm populations as inherently susceptible (i.e., most die), tolerant (many don't die), or resistant (few die) to acephate and carbaryl. However, while interesting and potentially useful, all this earlier work was a far cry from being able to say how effective an actual spray program was going to be; further integration of the toxicological and genetic information was needed.

In collaboration with Dr. Jo Ellen Force at the University of Idaho, and Dr. Carroll Williams at the USDA Forest Service, Berkeley, we recently developed a probability model to integrate information on variables known to affect insecticide efficacy in field applications and to simulate their cumulative effects. Model input includes insect species (Douglas-fir tussock moth or western spruce budworm), chemical (acephate or carbaryl), dose applied, genetic response level (susceptible, tolerant,

or resistant), age of insects (larval instar distribution), and foliage moisture condition (dry or wet from rain at various intervals just prior to or after spray).

A few examples of model output are shown here. For a carbaryl-tolerant Douglas-fir tussock moth population sprayed under dry conditions, low doses (70-140 g/ha) are most effective during the first 6 days after the caterpillars are first seen, and then after about 4 weeks (Fig. 3). Higher doses of carbaryl are effective any time. For carbaryl-susceptible Douglas-fir tussock moth populations, lower doses result in much higher mortality (Fig. 4).

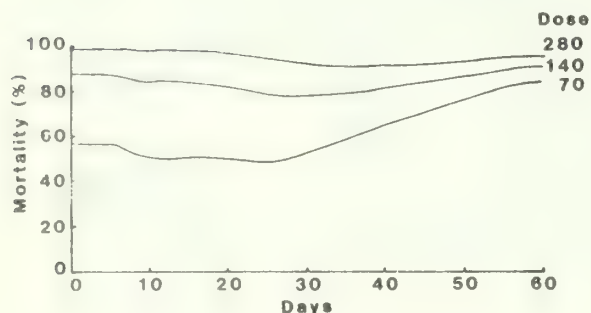


Figure 3.--Simulated mortality of carbaryl-tolerant Douglas-fir tussock moth treated with 3 dose levels of carbaryl in relation to days after egg hatch.

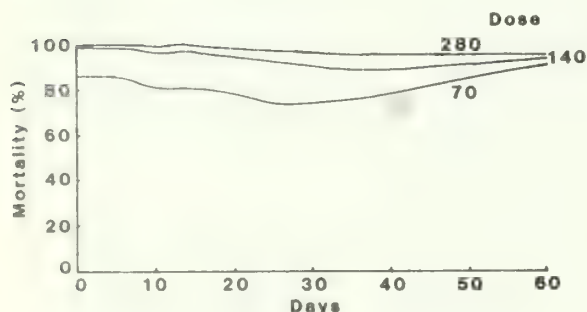


Figure 4.--Simulated mortality of carbaryl-susceptible Douglas-fir tussock moth treated with 3 dose levels of carbaryl in relation to days after egg hatch.

For acephate-tolerant western spruce budworm (the most common population type), low doses are nearly as effective as high doses during the 5th week after emergence (Fig. 5). When western spruce budworm are sprayed with carbaryl under dry conditions, mortality showed a consistent pattern regardless of dose (Fig. 6). Mortality fell steadily over development.

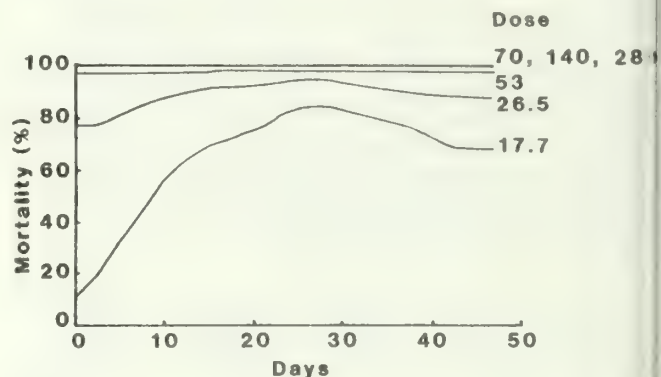


Figure 5.--Simulated mortality of acephate-tolerant western spruce budworm treated with 6 doses of acephate in relation to days after emergence of second-stage larvae from hibernacula.

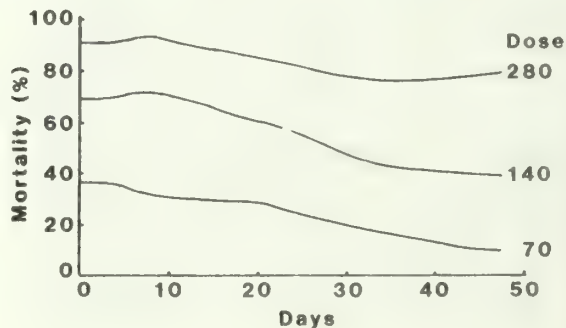


Figure 6.--Simulated mortality of carbaryl-tolerant western spruce budworm treated with 3 different doses of carbaryl in relation to days after emergence of second-stage larvae from hibernacula.

When acephate application to wet foliage was simulated, predicted mortality of insects of either species was drastically reduced for both tolerant and susceptible populations (Figs. 7 and 8).

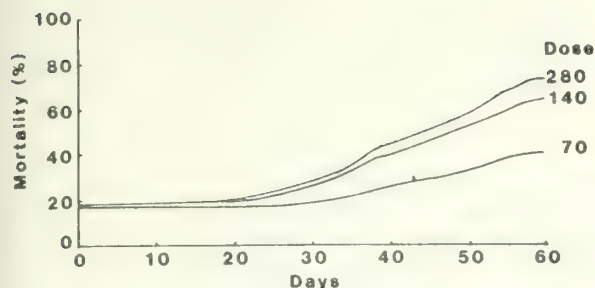


Figure 7.--Simulated mortality of acephate-tolerant Douglas-fir tussock moth on wet foliage to 3 different doses of acephate in relation to days after egg hatch.

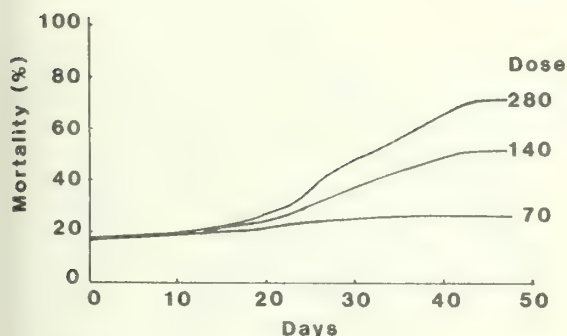


Figure 8.--Simulated mortality of acephate-tolerant western spruce budworm on wet foliage to 3 different doses of acephate (in relation to days after emergence of second-stage larvae from hibernacula).

Several generalizations can be drawn from these simulations. For example, for the Douglas-fir tussock moth, timing of spray application is crucial, especially when acephate is used. When carbaryl is used on the Douglas-fir tussock moth, it is particularly important to know the genetic makeup of the population to be sprayed. If the population is carbaryl-tolerant, spraying near the end of population development will give highest mortality. For the western spruce budworm, timing of spray is not as critical as dose. And if the foliage is wet at the time of spray, or if rain is expected soon after spray application, very low effectiveness will be obtained.

In terms of basic science, the model provides ideas and hypotheses for future research and testing. For example, we now recognize the need to evaluate the effects of host plant foliage on insecticide response. We also realize that the existing information used to predict and stimulate effects of rainfall must be expanded and refined. The model is also helping us provide after-the-fact explanation of why successful or unsuccessful results were obtained by a chemical control effort and, perhaps most important, is permitting more accurate forecasts of insecticide efficacy. Williams and Robertson (1983) found that the model predicts results of actual field applications with 73-95% accuracy. We have just completed development of a generalized, interactive ("user-friendly") model expanded to simulate efficacy of any chemical over time during seasonal development of a western spruce budworm or Douglas-fir tussock moth population. It is written in BASIC and can be operated on a minicomputer. This second-stage model will permit comparison of the effectiveness of a diversity of chemicals when decisions are being made in a control program. Next, the program will be adapted for use with other forest defoliators.

Information obtained with models such as these will enable forest managers to use chemical control more judiciously--choosing to use it when it will be most effective, choosing alternative methods when model output suggests that chemical control will be ineffective. Ultimately, time and effort can be saved, and environmental contamination by toxic chemicals reduced.

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DIFFERENTIAL POPULATION CHARACTERISTICS OF WESTERN SPRUCE BUDWORM¹

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Abstract.--Western spruce budworm populations differ significantly in their responses to carbaryl, an insecticide currently registered for their control. Although we interpret these differences in population response to be the result of cross-resistance between DDT and carbaryl, the possibility exists that the wide range of tolerance levels represents only natural variation. In either case, the underlying assumption of the insecticide registration process--that population responses are equal or vary only within relatively narrow limits--does not appear to be valid for carbaryl. We examine the evolution of this realization from the general assumptions that guided forest pest control practices beginning with the use of DDT in 1947.

INTRODUCTION

Spruce budworms (Choristoneura species) are among the most destructive defoliators in North America. In the eastern United States and Canada, the spruce budworm, C. fumiferana (Clemens), feeds primarily on balsam fir. White spruce, red spruce, black spruce, larch, hemlock and pines may also be defoliated (Baker 1972). The western spruce budworm, C. occidentalis Freeman, feeds primarily on Douglas-fir and white fir throughout the Pacific Coast States and British Columbia. Other hosts included grand fir, subalpine fir, western larch, Engelmann spruce, white spruce, and blue spruce (Turniss and Carolin 1977).

Western spruce budworm larvae feed on buds and new foliage. Sustained heavy feeding may cause almost complete defoliation in 4-5 years. Epidemics may result in decreased tree growth, tree deformation, top-killing, and tree death over extensive areas.

Prior to 1963, when its use was banned, DDT was heavily used for control of both eastern and western spruce budworm. For example, between 1952 and 1963, over 3,300,000 acres of forests in the northern Rocky Mountains were sprayed with DDT (Fellin 1983). The reasons for the frequent use were simple: DDT was readily available; it was cheap; it could be applied from aircraft; and it was effective.

Without DDT, and with the growth of integrated pest management practices for forest insects in recent years, the use of chemical control has decreased dramatically. However, several chemicals are still available for use against the spruce budworm and western spruce budworm. At present, carbaryl is one of the most commonly used insecticides in the United States. It is the active ingredient in such products as Sevin garden dust and flea powder. One reason for this widespread use is carbaryl's low toxicity to mammals and birds. The Sevin-4-oil formulation is registered by the Environmental Protection Agency for use as a forest spray for control of both spruce budworm and western spruce budworm (Hamel 1982).

The basic premise of the current insecticide registration process is that a chemical can be recommended for use at one rate for a given insect species because responses for populations of one species are equal or vary within relatively narrow limits. We have examined this premise in the case of western spruce budworm populations treated with carbaryl and have concluded that it is not

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valid. This premise is the latest in a series of assumptions that have guided forest insect control practices since the introduction of DDT. In our opinion, this assumption should be discarded in favor of a more biologically realistic approach to the use of insecticides as part of the integrated pest management systems for forest insects.

INSECT SYSTEMATICS AND PEST MANAGEMENT: PAST ASSUMPTIONS

Biological classification is a familiar subject. Living things are divided into two kingdoms, plant and animal. Kingdoms are divided into phyla, for example, the phylum Arthropoda. A phylum is divided into classes, for example, the class Insecta. A class, such as the Insecta, is divided into numerous orders. The order with which we are concerned is the Lepidoptera. An order, such as the Lepidoptera, is further divided into families. The spruce budworms are in the family Tortricidae. Other important families with respect to forest trees are the Lymantriidae, including such insects as the Douglas-fir tussock moth and gypsy moth, and the Geometridae, commonly called the inchworms or measuring worms. Families are divided into genera, such as the genus Choristoneura. A genus is divided into species, and a species is composed of populations.

From the time DDT began to be used routinely to control forest defoliators in 1947, forest entomologists assumed (on the basis of no data) than any chemical toxic to an insect species in any family would be equally toxic to the other species in that family. This assumption probably resulted from the fact that DDT was toxic to virtually every insect pest from the body

louse to the budworm when it was first used and before resistance began to appear. We were the first to question this premise when we compared to responses of various forest geometrids (Table 1) (Robertson et al. 1974). We concluded that the large differences in LD₅₀ values, sometimes over 100-fold, clearly showed the risk involved in predicting insecticide toxicity to one species on the basis of data obtained for a different genus in the same family.

We next examined another presumption, that is, that species in the same genus would have equal responses to any chemical. In 1978, we tested species in the genus Choristoneura (Robertson et al. 1978). Table 2 is a sample of our results. These data are for carbaryl, and show almost a thirty-fold difference in response between the most and least susceptible species. Our overall results are shown in Table 3. Since the hypothesis of equality (Savin et al. 1977) was not accepted among species for any of the 22 chemicals tested,

Table 2.--Responses of Choristoneura conflictana (C), occidentalis (O), lamertiana (L) and viridis (V) to carbaryl

Species	LD ₅₀ (95%CL) ^a
C	3.65(2.92-4.35)
O	19.9(14.5-26.5)
L	30.6(11.5-44.5)
V	109(6.90-325)

^aµg/g body weight. 95% CL are 95% confidence limits.

Table 1.--Decreasing order of susceptibility at LD₅₀ of forest geometrids^a to eight insecticides

Insecticide	Most susceptible	Times less susceptible		
		1.3-12	30-60	128- 417
Bioethanomethrin	E	--	P(50) ^b	C(167)
DDT	L	E(1.3)	A(32)	C(142)
Malathion	L	E(7.0)	P(>29)	A(152), C(>417)
Mexacarbate	E	L(2.0)	A(30), C(47)	P(128)
Phosmet	E	--	C(34)	--
Phoxim	E	C(12)	P(38)	--
Pyrethrins	E	L(2.0), P(7.0)	A(40), C(60)	--
Tetrachlorvinfos	E	C(6.9)	A(38), P(38)	--

^aAbbreviations for species are: A = Alsophila pometaria; C = Calocalpe undulata; E = Ennomos subsignarius; L = Lambdina fiscellaria lugubrosa; P = Paleacrita vernata.

^bValue in parenthesis indicates LD₅₀ less susceptible species LD₅₀ most susceptible species.

Table 3.--Summary of tests of the hypothesis of equal responses among Choristoneura species

Type of insecticide	Number tested	Number of species compared	Hypothesis accepted for any chemical?
Carbamate	4	2-6	No
Chlorinated hydrocarbon	1	6	No
Organophosphorous	11	2-4	No
Pyrethroid	6	2-5	No

concluded that the genus was not the taxonomic level at which to generalize.

The next level we considered was the species. In 1978, we examined the responses of Douglas-fir tussock moth populations to insecticides. Responses of these populations to carbaryl provide an example of our findings (Table 4).

Table 4.--Responses of California (C), Montana (M), New Mexico (NM), and Oregon (O-1 and O-2) Douglas-fir tussock moth populations to carbaryl

Population	LD ₅₀ (95%CL) ^a
C	25(21-30)
O-1	56(38-120)
O-2	51(30-170)
M	30 b
NM	160 b

^aµg/g body weight. 95% CL are 95% confidence limits.

^bData too heterogeneous to provide useful 95% CL.

Table 5 shows the overall results of our experiments. Clearly, equal responses were rare. This was our first indication that the generalization that population responses are very similar and usually equal was not valid. However, further work was necessary before we were absolutely certain of this conclusion.

Our next investigation also concerned Douglas-fir tussock moth populations. This time, we considered populations and sibling

Table 5.--Results of tests of the hypothesis of equal responses among Douglas-fir tussock moth populations

Insecticide	Populations tested	Hypothesis accepted for any chemical?
Bioethanomethrin	W,O-1,C,NM	No
Carbaryl	C,O-1,O-2,M,NM	No
DDT	W,C,O-1,O-2,M,NM	No
Mexacarbate	W,C,O-1,O-2,M,NM	No
Phoxim	W,C,O-2,NM	No
Pyrethrins	W,C,O-1,O-2,M,NM	No
Trichlorfon	O-2,M,NM	No

groups, the genetic products of a single pair mating (Stock and Robertson 1979). We also related genetic characteristics to response. The results of the population tests are shown in Table 6. Once again, population responses were not generally equal. The sibling group responses were very revealing (Table 7). Sibling group responses are highly variable and appear to be the ultimate unit of variation of population response. These responses are related to variation in frequency of an esterase isozyme detectable by electrophoresis.

Table 6.--Responses of Douglas-fir tussock moth populations to acephate and carbaryl

Population ^a	LD ₅₀ (95%CL) ^b
1. Acephate	
NM	52.4(46.7-57.6)
LFB	51.8(46.2-57.4)
ED	54.4(48.1-59.6)
LAB	55.5(45.0-65.7)
2. Carbaryl	
NM	32.5(15.8-62.6)
LFB	25.3 (7.4-48.2) ^c
ED	22.4(12.8-32.5)
LAB	41.8(25.0-87.4)

^aAbbreviations for populations are: NM = Medio Dia Canyon, Cibola National Forest, New Mexico; LFB = Lowry Air Force Base, Denver, Colorado; ED = east Denver, Colorado; LAB = laboratory colony, Berkeley, CA.

^bDosage expressed as µg/g body weight. 95% CL are 95% confidence limits.

^cData too heterogeneous to compute 95% CL. 90% CL listed.

Table 7.--Toxicity of acephate and carbaryl to sibling groups of a Douglas-fir tussock moth population

Sibling group no.	LD ₅₀ (95%CL) ^a
1. Acephate	
3	45.1(b)
4	36.6(b)
5	47.2(39.2-56.4)
9	75.8(63.0-101)
8	147.7(b)
11	54.4(48.1-61.1)
13	76.0(57.9-93.6)
14	54.9(39.4-75.2)
15	59.2(44.7-66.8)
2. Carbaryl	
2	21.3(10.9-31.8)
3	48.8(31.2-168)
6	14.1(b)
7	20.7(b)
11	2.4(b)
12	17.1(b)
14	85.1(b)
15	172.0(b)

^aDosage expressed in µg/g body weight. 95% CL are 95% confidence limits.

^bData too heterogeneous to provide useful 95% CL.

On the basis of the second Douglas-fir tussock moth population study, we concluded that, from a practical aspect, adoption of routine genetic assays as part of population surveys prior to implementation of control operations could provide estimates of population response to various insecticides. Initially, joint genetic/toxicological assessments might be performed as part of each population survey. Larvae from many randomly selected egg masses could be reared to the fourth instar in the laboratory, their response to a particular insecticide determined, and survivors and control larvae from each sibling group subjected to electrophoretic analysis. Once sufficient data from concurrent genetic and toxicological evaluations were obtained, direct extrapolation from a pre-spray genetic survey to a dosage required for desired level of mortality in the field could be achieved. Ultimately, such matching could minimize overdosing and environmental contamination on one hand, and insufficient levels of control on the other.

DIFFERENTIAL POPULATION RESPONSES OF WESTERN SPRUCE BUDWORM

Over the past three years, we have examined 11 widely distributed population samples of western spruce budworm (Robertson and Stock 1983). The general results of these experiments are shown in Table 8. We have identified five distinct response levels among these populations.

Table 8.--Relative responses of western spruce budworm population samples to carbaryl

Population (State-year)	Tolerance Ratio ^a
Idaho-1981a	1.0
Washington-1981a	1.2
Washington-1980a	1.6
Idaho-1980	1.8
Washington-1981b	2.6
New Mexico-1981	4.0
Arizona-1981	4.2
Idaho-1981b	4.6
Montana-1981a	6.8
Washington-1980b	8.8
Montana-1981b	17.9

^aLC₅₀ population ÷ LC₅₀ Idaho 1981a.

The Idaho-1980, Idaho-1981a, Washington-1980a, Washington-1981a, and Washington-1981b constituted the first group at the level of highest susceptibility.

At the next level, the Arizona-1981 and New Mexico-1981 populations composed the group of second to the highest susceptibility. The next level was occupied by one population sample, Idaho-1981b.

At the level of second most tolerance, responses of the Montana-1981a and Washington-1980b samples well equal to one another but not to those of the Idaho-1981b group. Finally, the Montana-1981b sample was most tolerant.

How can this kind of variation be explained? Estimates of natural variation within western spruce budworm populations suggest that 2-fold variation in responses is about as high as one might expect. The 18-fold difference we see, therefore, does not seem to be natural.

We have examined a number of variables among the treatment sites, and have concluded that the

vious spray history of the areas has resulted in the population responses we observed. The treatment histories are shown in Table 9. The phenomena we believe account for differential responses are resistance, or genetic selection as a result of the use of one chemical repeatedly, and cross resistance, by which exposure to one chemical confers increased tolerance to a totally different chemical.

Table 9.--Relationship of response to carbaryl and previous treatment history at collection sites

Population (State-Year)	Insecticide used in area	LC ₅₀ (mg/ml)
Idaho-81a	None	2.2
Washington-81a	Fenitrothion 1975; Malathion 1976; Carbaryl 1977	2.7
Washington-80a	Fenitrothion 1975; Malathion 1967; Carbaryl 1977	3.5
Idaho-80	None	4.0
Washington-81b	None	5.8
New Mexico-81	DDT 1963; Malathion 1966	8.7
Arizona-81	DDT 1958	9.3
Idaho-81b	Carbaryl 1979	10.0
Montana-81a	DDT 1957; Carbaryl 1975	15.0
Washington-80b	Malathion 1967; Carbaryl	19.4
Montana-81b	DDT 1957	39.4

With one exception, all of the population samples which were significantly more tolerant than the most susceptible group were collected from areas previously sprayed with DDT. Over-rid on this general pattern is the use of other chemicals on some of the sites. None of the Idaho samples originated from an area sprayed with DDT. Idaho insects from an area sprayed with carbaryl in 1979 were almost five times more tolerant than the sample collected from an unsprayed area in 1981 and 2.5 times more tolerant than a sample collected from the same sprayed area in 1980. Among the Washington

samples, which were also from sites not sprayed with DDT, the sample collected from an area treated in successive years with three different chemicals and the sample from an untreated site varied by 2.2-fold. However, the sample from the Washington site sprayed with malathion and carbaryl was 3.3 times more tolerant than the sample from the untreated site, and 7.2 and 5.5 times more tolerant than the sample from the triple treatment site that was sampled in 1980 and 1981, respectively. Based on these differences, one can hypothesize that the high level of tolerance in the Idaho 1981b population is related to the previous use of carbaryl in that area. The response of the apparently resistant Washington population sample from the double treatment site might reflect cross-resistance between malathion and carbaryl, a phenomenon which was negated at the triple treatment sites by the prior use of fenitrothion.

The general pattern of greater tolerance in samples from DDT-treated sites may also be a result of cross-resistance. Cross-resistance between DDT and carbaryl has been described in the housefly (e.g., Plapp et al. 1979). The gene responsible for cross-resistance confers high levels of microsomal mixed function oxidase activity to resistant individuals (Plapp 1976). These enzymes are known to be primarily responsible for carbaryl metabolism. In other words, the resistant individuals have more enzyme by which to detoxify the insecticide. We postulate that a similar genetic mechanism occurs in the western spruce budworm. If this is the case, the tolerance level of the New Mexico and Arizona populations represents an intermediate shift between the natural, untreated, population responses and the more extreme tolerance levels attained by the Montana population. The difference in response of the two Montana populations is slightly greater than we would expect from natural variation alone. In addition, the greater tolerance of the group collected in an area only sprayed with DDT compared to the group from an area sprayed both with DDT and carbaryl is somewhat puzzling. However, the two collection sites are quite close to one another and interbreeding may have been extensive. Our hypothesis is that exposure to both DDT and carbaryl has shifted the population response as a whole into a higher tolerance level than that of the Arizona and New Mexico populations.

CONCLUSION

More research is needed in this area, not just with the western spruce budworm but with the spruce budworm, Gypsy moth, and Douglas-fir tussock moth. Carbaryl has been applied year after year in Maine, for example, and to our

knowledge no one is monitoring the extent to which spruce budworm population responses might be changing as a result.

Finally, the insecticide registration process could be improved by incorporating consideration of the range of responses of insect populations to a chemical and not simply by making a generalization for an entire species.

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NUCLEOPOLYHEDROSIS VIRUS TRANSMISSION IN THE GYPSY MOTH,

LYMANTRIA DISPAR (LEP: LYMANTRIIDAE)¹

Kathleen S. Shields²

Abstract.--The gypsy moth (Lymantria dispar L.), the most important defoliating insect of hardwood trees in the eastern United States, is susceptible to a naturally occurring nucleopolyhedrosis virus (NPV). The Forest Service registered the NPV product GYPCHEK for use as a biological control agent against the gypsy moth, but effective use of GYPCHEK in pest management depends on a better understanding of the many factors involved in NPV infection, transmission, and initiation of epizootics. Recent research in these areas is discussed.

If you have not already met, I would like to introduce you to the gypsy moth, Lymantria dispar. The insect's life cycle starts with hatching of the egg masses in late April or early May. The larvae go through five stages, females go through six, and then pupate. The moths emerge in the middle of July and mate; then the male lays an egg mass containing up to 1,000 eggs. The eggs embryonate and 1st-stage larvae overwinter in a diapause state within the egg. There is only one generation each year.

The gypsy moth is not a native species. It was imported into the United States from France by Professor Leopold Trounelt, an astronomer and naturalist who envisioned utilizing the insect for silk production (Medford Mercury Press 1906). In 1869, some larvae escaped from a window of Trounelt's laboratory in Medford, Massachusetts (Forbush and Fernald 1896), and 10 years later an established gypsy moth population was completely stripping the leaves from large shade trees in residential areas surrounding the release site (Medford Mercury Press 1906). The gypsy moth is considered the most important defoliating insect of hardwood trees in the eastern United States (McManus et al. 1979). In 1981, nearly 13 million acres of woodland were defoliated by the gypsy moth, compared with 5 million acres defoliated in 1980, and the infestation is still spreading south and west (McManus and Riddle 1982).

In addition to being a forest pest, the gypsy moth is also a public nuisance. The larvae are endowed with an abundance of setae that are a type of pruritic dermatitis in exposed individuals (Shama et al. 1982), and in heavily infested areas it is difficult to avoid exposure to gypsy moth larvae. Young larvae hang from thin silk threads and are dispersed by the wind; older larvae and their droppings make backyards, parks and recreational areas inhospitable.

Since the first major gypsy moth outbreak in 1889 (Forbush and Fernald 1896), attempts have been made to eradicate the insect with various pesticides. But many problems resulted from the use of synthetic pesticides, and after the 1972 Environmental Protection Agency (EPA) ban on the use of DDT in the United States, more emphasis was placed on control of the gypsy moth through the use of natural agents.

The gypsy moth is susceptible to a number of natural disease agents (Lewis and Etter 1978), including a specific nucleopolyhedrosis virus (NPV). The virus disease was first reported as "wilt disease" by Reiff in 1911 and by Glaser in 1915, but the causative agent was not demonstrated until 1947 (Bergold 1947). Since that time, extensive world-wide research has been directed toward using this virus as a biological control agent for the gypsy moth.

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Gypsy moth NPV is in the genus Baculovirus, family Baculoviridae (Wildy 1971). The host range of NPVs is restricted to invertebrates, and principally to the insects (Tinsley 1979). Most NPVs have been isolated from species of Lepidoptera, but some have been isolated from Orthoptera, Neuroptera, Trichoptera, Coleoptera, Hymenoptera, and Diptera (David 1975) and an NPV has been found in the pink shrimp, Penaeus duorarum (Couch 1974). NPV host specificity within the Lepidoptera varies. For example, the NPV originally isolated from the alfalfa looper, Autographa californica, is one of the least host-specific NPVs and is known to infect many species of Lepidoptera (Vail et al. 1971), while gypsy moth NPV seems to be selective for only the gypsy moth (Lewis 1981). The NPVs found in the Lepidoptera do not seem to infect other orders, and vice versa (Tinsley 1979).

The physical and biochemical characteristics of NPVs are quite different from those of viruses that infect vertebrates and plants (Tinsley 1979). The term nucleopolyhedrosis refers to the replication of these viruses in host cell nuclei, and the formation there of large numbers of characteristic polyhedral inclusion bodies. The inclusion bodies of gypsy moth NPV are irregular in shape and range from 1 to 10 μm in diameter. They contain many rod-shaped, enveloped viral particles (virions) surrounded by a paracrystalline matrix of protein. The genome is a large, circular, double-stranded DNA (Mazzone and McCarthy 1981). The polyhedral inclusion body protects the infectivity of the virions and purified inclusion body preparations can be stored, over a wide temperature range, either as dry powders or as suspensions (Lewis and Rollinson 1978). However, the inclusion body paracrystalline matrix protein can be readily dissolved in alkaline solutions, and virions released (Bergold 1963).

The characteristics of baculoviruses in general, and of this NPV in particular, suggest several reasons why gypsy moth NPV could be considered a suitable biological control agent: (1) it has an extremely limited host range and is unrelated to viruses that infect vertebrates and plants; (2) it occurs naturally and has been implicated as a cause of epizootics; (3) its polyhedral inclusion bodies can be produced in large quantities, stored for long periods, and easily formulated for aerial or ground application.

In 1974, the U.S. Department of Agriculture established an accelerated gypsy moth research, development, and application program. Within this program the Forest Service selected gypsy moth NPV for development as a viral pesticide, and in 1978 obtained EPA registration of the NPV product Gypchek. It was the first NPV product registered by the EPA for use on deciduous hardwood trees in the Northeast--the most heavily populated area of the United States.

Gypchek has many positive attributes but further development and improvement of formulations and application methods are necessary to optimize their effects. And ultimately the effective use of Gypchek in gypsy moth control depends on an understanding of the epizootiology of the virus disease, both natural and artificially induced (Lewis 1981). Information on the many factors involved in the course of NPV infection and in NPV transmission within and between generations of the gypsy moth is needed to construct an epizootiological model to predict population fluctuations and to better assess the role of natural NPV and of applied Gypchek in integrated pest management schemes.

Any epizootiological model has to start with infection of the host. Although viruses can be acquired transovarially, through parasitism, as a result of injury, oral infection of larvae seems to be the most common route of entry of NPV into an insect host (Granados 1980). When gypsy moth larvae consume NPV-contaminated foliage, the polyhedral inclusion bodies slowly dissolve in their alkaline digestive fluids, liberating virions in the digestive tract. The dissolution process is believed to be initiated by pH and possibly by some enzymatic degradation (Tinsley 1979). The liberated virions then presumably pass through the peritrophic membrane which lines the midgut, and come into contact with the midgut epithelium. Passage of virions through gypsy moth midgut has not been documented but since virions have been detected in the hemocoel within 2 hours of NPV ingestion (Shields 1983), it seems likely that they either traverse the intercellular spaces or enter the hemocoel by direct passage through epithelial cell cytoplasm.

Once within the hemocoel, virions enter hemocytes and replicate. Five hemocyte types are present in gypsy moth larvae: prohemocytes, plasmatocytes, coagulocytes, spherulocytes, and granulocytes; only the first three types seem susceptible to NPV infection. Virions apparently gain entry into hemocytes by viropexis, an engulfment process similar to phagocytosis. The viral particles are released from phagocytic vesicles into the cytoplasm has not been determined, but it may be through simultaneous lysis or rupture of vesicle membrane and viral envelope.

Viral particles have often been found closely associated with cytoplasmic microtubules which may be involved in their vectorial movement to the cell nucleus where the virus replicates. After the viral genome is uncoated, there is an eclipse period during which no viral units can be detected. During the eclipse period, the virogenic stroma (an accumulation of electron-dense chromatin-like material) appears and progeny viral particles are assembled in this region.

Once assembled, viral particles seem to acquire envelopes by a variety of means. Some are enveloped in the cell nucleus by newly synthesized viral envelope material. These virions are apparently restricted to the cell nucleus and seem destined for occlusion within polyhedral inclusion bodies. These virions probably have no role in secondary infections in the host. Other viral particles bud from the nucleus in long tubules of nuclear membrane and extend to the plasma membrane of the cell. Other viral particles bud through the plasma membrane into the cytoplasm, enclosed in a vesicle of outer nuclear membrane. Release of viral particles from these vesicles has not been observed, but it has been suggested that they may pass through breaks in the membranes (Granados et al. 1980). The released viral particles bud through the plasma membrane into the hemocoel. A part of the plasma membrane initially contacted by the viral particle develops a new morphology (surface spikes of viral glycoproteins) which is retained on that end of the newly acquired plasma membrane-derived viral envelope. Peplomers have not been observed on viral envelopes in host cell nuclei or on nuclear membrane-derived envelopes of viral particles in the cytoplasm (Adams et al. 1977). It has been suggested that virions exhibiting a peplomer structure on the viral envelope are responsible for secondary and succeeding infections within the hemocoel (Adams et al. 1977, Granados 1980, Granados and Lawler 1981).

Although polyhedral inclusion bodies are produced in the nuclei of gypsy moth hemocytes, they are produced in much greater numbers in the nuclei of cells of the fat body, tracheae, and epidermis, with the fat body probably producing the greatest numbers. Viral particles produced in these tissues apparently are routinely enveloped in the nucleus and occluded. Enveloped viral particles do not seem to be released by polymerizing protein, even though polymer may be present in the nucleus when inclusion bodies are forming. Polymerizing protein with a regular crystalline lattice structure is deposited around and between virions. Increasing numbers of virions become occluded, and the ultimate size of the polyhedral inclusion bodies may be determined by depletion of virus protein monomer (Harrap 1972, Tinsley 1979).

In late stages of infection, cell nuclei of susceptible tissues become greatly enlarged and are filled with polyhedral inclusion bodies. The plasma membrane and plasma membrane may rupture, releasing inclusion bodies and not-yet-occluded virions into the hemocoel. Eventually, all susceptible tissues are infected. The lethal incubation period for NPV in the gypsy moth is 10 to 14 days, but infected larvae often show no symptoms of the disease for much of this period.

In very late stages of infection, larvae will stop feeding and become sluggish, and their integument often takes on an oily appearance. At death, larvae often hang by a proleg in an inverted position. As a result of cell lysis, the body contents are now liquified and are contained only by the very fragile integument, which easily ruptures, liberating masses of polyhedral inclusion bodies.

The body fluids of the host insect seem to provide some degree of protection to the virus against inactivation by solar radiation (Tinsley 1979). Gypsy moth NPV remains infectious at high levels for at least 1 year on environmental environmental surfaces (Doane 1975, Podgwaite et al. 1979). But exactly how the disease is spread among individuals and how NPV epizootics occur are not well understood.

Obviously, larvae can become infected by ingesting NPV-contaminated foliage, and this presumably happens in natural populations. Laboratory studies indicate that gypsy moth larvae can transport NPV from contaminated environmental surfaces to a food source (Podgwaite et al. 1981). Parasites and predators may also have a role in NPV transmission. Some entomophagous parasites can transmit NPV from infected to healthy gypsy larvae (Raimo et al. 1977), and positive correlations have been found between NPV mortality and the prevalence of various entomophagous parasites (Reardon and Podgwaite 1976; Godwin and Shields 1983). Several species of birds and mammals that are predators of the gypsy moth have been shown to pass and disperse active gypsy moth NPV within the environment (Lautenschlager and Podgwaite 1979). Much evidence suggests that this NPV can be transmitted from generation to generation of the gypsy moth by surface contamination of egg masses (Doane 1969, 1970), but it is not known whether NPV is deposited on the eggs by the female during oviposition or whether NPV in the environment is transported by wind or rain onto egg masses to infect emerging larvae. Although all of these types of NPV transmission undoubtedly occur in natural gypsy moth populations, to what extent they occur and their relative significance in NPV epizootiology remain to be determined. Much of this work is ongoing.

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THE SHORT- AND LONG-TERM EFFECTS

OF INSECT ATTACKS ON TREES¹

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Abstract.--Many people view all insects, except perhaps for honeybees and butterflies, as harmful pests. This view extends to those insects occurring and feeding on trees. It is true, however, only if one considers the short-term effects of insect attacks. Nevertheless, the effects on the forest as a whole must be considered over the long as well as the short term. An example is presented of the effects of ambrosia beetle attack on black walnut trees in which the long-term biological and economic effects are minimal.

About 75% of all the different kinds of animals alive today are insects: approximately 1 million species of insects have been described with an equal or larger number yet to be described. One estimate of the total number of insect species alive in the world is 30 million (Erwin 1982), although most estimates are between 1.5 and 3 million. Compare this figure to the 9,000 species of birds or 4,200 species of mammals. Insects are an important part of the environment in which we live because of sheer numbers and because of the economic impact they have on human society. The economic or destructive aspects of insects' presence in our society receive major emphasis because of the staggering dollar values attributed to insect-caused losses. The total annual value of insect damage to food and household products and to insect-transmitted diseases was estimated at \$3.5 billion in 1957 (latest available figures) in the U.S. alone (Metcalf et al. 1962). The damage to forest trees and forest products was estimated at \$2.5 billion in 1957 dollars (Metcalf et al. 1962).

Beneficial insects receive less attention and, therefore, their contributions to society usually remain unquantified. One exception is

insect pollinators. Their value for producing fruit and seed crops was estimated at \$4.5 billion in 1958 (Metcalf et al. 1962).

The number of destructive insects is small compared to the total number of species. Baker (1972) reported that 154 different insect pests reached outbreak status in eastern forests during a 10-year period. In southern Illinois, at least 300 species of insects occur on the black walnut (*Juglans nigra* L.) trees but only about 10% occur commonly (Nixon and McPherson 1977). These common species may or may not be potential pests, however. That they occur commonly and may feed on the trees does not necessarily mean they are harmful insects.

This paper is divided into two parts. The first briefly describes the short- and long-term effects of insect attacks on trees in general. The second gives a specific, although hypothetical, example concerning an insect pest of black walnut trees and the economic and biological effects of attack.

INSECT ATTACK ON TREES

Short-term effects

Insects that use trees as a food source or for habitat cause both direct and indirect short-term effects. Immediate and direct effects of insect attacks on trees occur because of chewing, boring, or sucking activities of the insects. These result in loss of tree biomass in the form of leaves, sap, seed, or wood; reduced height or diameter growth; reduced resistance to diseases or other insect pests; or death. Indirect effects of insect attacks occur because the forest environment

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and those organisms using the forest are affected. The immediate indirect effects include reduced recreational and esthetic values, increased fire hazards, altered habitat for wildlife, altered forest management goals and costs, degrade of forest products, and stress and anxiety in humans.

Immediate, direct effects of insect attacks on trees are the most easily and commonly studied by entomologists and by foresters and, therefore, receive the most emphasis. The short-term direct effects are often used by entomologists and pest control decision-makers to justify the need for control of forest pests causing recurring or widespread damage. The indirect effects, however, are acknowledged by researchers and forest managers but much less commonly studied because of lesser interest and because of greater difficulties involved in studying them. Therefore, little data are available on the importance of the indirect effects.

Long-term effects

The long-term effects of insect attacks on trees are less easily classified as direct or indirect because both individual trees and the entire forest are affected. These effects may include increased tree biomass, increased height and diameter growth, reduced competition, improved nutrient cycling, altered stand composition and plant diversity, and altered management goals.

Long-term effects of insect attacks also have received little inquiry, primarily because of the long time that must be devoted to studies of this type. Evidence is available, however, that some apparently destructive insects are actually beneficial to trees in the long term as opposed to the evidence that insects are harmful to trees in the short term. For example, insects such as the Douglas-fir tussock moth or the forest tent caterpillar are leaf-feeders that defoliate thousands of acres of trees when in outbreak status. Yet researchers have found that a few years after defoliation trees actually showed greater height and diameter growth than they did before defoliation (e.g., Brookes et al. 1978). This has been shown to be a result of increased nutrient cycling due to high concentrations of nutrients in dead insects, insect frass, and unused food parts (Mattson and Addy 1975). Another reason for improved tree growth is that defoliation causes an increase in the amount of light entering the forest stand and apparently causes new leaves to be larger; these new leaves have greater photosynthetic areas and a corresponding greater efficiency in the photosynthetic process.

Both short- and long-term effects of insect attacks must be considered in the process of deciding how serious a potential pest may be. Other considerations include the age of the trees (how near to harvesting and how much time the trees have to recover before harvesting) and the long-term management goal for the trees.

Following is a hypothetical example of an insect problem on black walnut trees growing in managed plantations and the implications of this insect over both the short and long terms.

AN EXAMPLE FROM BLACK WALNUT

The trees: Black walnut is the most valuable hardwood species in the U.S. because of its color, durability, and excellent workability for furniture-making. It occurs throughout most of the eastern U.S. except for the extreme northern and southern parts. Because of its popularity and desirability as a furniture wood, not many high quality trees remain in natural forest stands. Therefore, many persons are planting black walnut in managed plantations for investment purposes and to maintain a lasting supply of this beautiful wood.

A walnut grower must invest considerable time and money into establishing his or her plantation. Establishing a plantation includes preparing a site for planting, buying and planting the trees, and caring for the trees for at least the first 3 years after planting. These costs do not include the cost of the land itself, taxes on the land, or any other expenses incidental to the plantation (i.e., purchasing a tractor or other equipment for site preparation).

Assume a walnut grower wants to establish a 5-acre black walnut plantation with nursery-run seedlings planted at a 10- x 10-foot spacing, equivalent to 436 trees per acre. The total cost for planting 5 acres or 2,180 walnut trees is \$1,301.75 (Table 1). The investment of \$1,301.75 is one that must be carried until harvest time or until some income can be realized from the trees. For black walnut the time period to harvest is estimated to be from 60 to 80 years.

The management goal for the plantation is to grow trees to about 20 inches in diameter and harvest at about age 60. Based on the expected future value of black walnut at present-day prices, the income from the plantation is expected to be about \$2,600 after 48 years and \$30,500 at the end of 60 years (Table 2).

Table 1.--Costs of establishing a 5-acre black walnut plantation during the first 3 years^{a,b}

Cost of trees: \$0.28/tree x 2,180 trees	\$ 610.40
Site preparation costs: \$27.06/acre x 5 acres	\$ 135.30
Planting costs: \$45.48/acre x 5 acres	\$ 227.40
Weed control costs: \$21.91/acre/year x 5 acres x 3 years	\$ 328.65
TOTAL	\$1,301.75

^aAssuming that standard nursery stock was planted at a 10- x 10-ft. spacing, which is equivalent to 436 trees per acre or 2,180 trees on 5 acres.

^bCosts are taken from Marty and Kurtz (1981) and are the average costs in each category.

Table 2.--Expected income from a 5-acre black walnut plantation^a

No. trees removed	Expected income ^b
1,090	-
359	-
531	-
65	\$ 2,600
135	\$30,510

^aAssuming the trees are allowed to grow to 6 inches in diameter before final harvest at age 60, and the plantation is thinned at ages 30, 40, and 48 (after Marty and Kurtz 1981).

^bExpected income figures represent 1981 stumpage price estimates projected forward at 5% annual inflation rate (the inflation rate of walnut lumber prices is higher than the general inflation rate).

The insect problem: Now consider an insect problem that affects the trees at age 4. The ambrosia beetle *Xylosandrus germanus* attacks trees in May and June of the 4th year after planting. In this hypothetical example, assume the beetle attacks 20% of the trees, causing dieback and apparent death of the trees.

X. germanus is an ambrosia beetle that attacks many species of trees, including black walnut. It attacks dying trees, recently cut tree stumps, and young trees that are apparently healthy. In this latter situation, it attacks plantation trees between the ages of 3 and 8. *X. germanus* attacks trees in this age group because it seems to prefer trees between about 1 and 2 m tall. The beetles attack at the base of the tree in mid-spring, causing rapid dieback and dieback (Weber 1982).

An important point is that the tops of trees die back but the roots are usually still alive. Attacked trees often sprout back from below the attacked points and seldom do whole trees die. In southern Illinois, none of almost 400 trees had died 3 years after attack by the beetle although most of them appeared to be dead immediately after attack (Weber 1982). Because of the dieback, attacked trees showed significantly reduced height and diameter growth in the year of attack. Two years later, however, new sprouts from the root systems of the attacked trees were actually growing faster than unattacked trees. The attacked trees recovered well, with the sprouts replacing the original trees (Weber and McPherson, in press).

Furthermore, *X. germanus* does not usually attack sprout trees and, although it may be present in a plantation for several years, it is a serious problem for only 1 or 2 years.

An initial estimate of the losses the beetle caused in this hypothetical example is about \$6,400 (Table 3). The \$275 immediate loss is based on the assumption that the trees must be replanted. But generally the trees do not die and thus do not need to be replanted. Therefore, the loss of \$275 is not real. One potential cost, however, is the necessary pruning to remove excess sprouts from the attacked trees. This cost is about \$15 for 436 trees (after Marty and Kurtz 1981).

The loss of \$6,102 represents the assumed loss of merchantable trees at harvest time (Table 3). Again, the trees were not actually lost. Moreover, looking more closely at the final harvest figures, only 135 out of 2,180 (or 6%) trees planted will actually be harvested at age 60. This means that 94% of the trees will be removed earlier in various thinnings because they are too small, too poor quality for prime walnut grades, or too close to a more desirable tree nearby. The point is

Table 3.--Losses due to ambrosia beetle attack on black walnut trees at age 4^{a,b}

Replacement costs for 436 trees	\$ 275.36
20% of expected income at harvest time	\$6,102.00
Total losses due to beetle attack	\$6,377.36

^aAssuming a 20% attack rate in a 5-acre plantation.

^bBased on average management costs obtained by Marty and Kurtz (1981).

that only a few trees are selected as final crop trees and many are culled out along the way. Because of the rapid recovery potential of most black walnut trees after beetle attack, they probably will have the same chance as those not attacked to become final crop trees. If the recovery potential is lower, the selection opportunities will be reduced somewhat. The loss, however, will be much less than initially estimated.

CONCLUSION

From the evidence, therefore, I conclude that the long-term effects of ambrosia attack on black walnut trees are minimal, both biologically and economically. This is so because the ambrosia beetle attacks trees when they are young and have time to recover.

Insects do cause problems on trees and some insects on some species of trees may have serious effects. However, researchers and tree growers must balance the short-term effects and losses against the less serious long-term ones before recommending potentially expensive control measures.

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PANEL QUESTIONS

FIRST SESSION: Biological Aspects of
Forest Pest Control

QUESTION (P.M. Hanson): Under optimal spraying conditions there are points when relatively low dosages caused high mortality depending on the compound you used or the insect age. I was wondering what practical or laboratory work has been done to investigate use of the model when joint applications of pesticides are a possibility. In other words, would the model be at all helpful or sophisticated enough to give a compromise?

RESPONSE (M.W. Stock): What do you mean by joint application:

QUESTION (P.M. Hanson): Two chemicals.

RESPONSE (M.W. Stock): Yes, we could do it. We've just completed six years of testing on mixtures of chemicals; we now have a data base that we could use. It's just that some more work needs to be done to see if using mixtures would actually have an economic benefit. We are doubtful that it would be useful. But basically with the model, all you need is the right data base.

QUESTION (P.M. Hanson): You didn't mention it today, but in your paper you said that the accuracy of the model was 73-95%, and I was wondering if you have any suspicions of what might have caused the variations from 100%. In other words, where would you look to find additional variables to make the model stronger?

RESPONSE (J.L. Robertson): Let me start. First of all I'd say the field test data was wrong - obviously. Mollie can take it.

(M.W. Stock): In any model like ours, you start with very simplistic assumptions and you put in only certain things to see how accurate it is. Then you say maybe if we add something it will be more accurate. This is just a beginning.

QUESTION (P.M. Hanson): What sort of variables do you think you might add?

RESPONSE (M.W. Stock): Some examples are better information about rainfall, the amount of cover protection of the foliage. We don't have these. I mention them as possible variables. Canopy cover is something to be considered, but we don't have any information on that in the model. There are all kinds of variables related to the spraying technology itself. So there are many more things that could be put into this to make it more accurate. So what we have right now is very rudimentary sort of model. But that is the way you start these things. If you put everything in to start with and it wasn't accurate you wouldn't even know where to start looking for the problem.

QUESTION (P.M. Hanson): I was wondering if either of you have been interested in expanding the model to account for subsequent changes the following years?

RESPONSE (M.W. Stock): It's something we can do eventually, but we don't have the data yet to be able to put the parts together. In other words when you spray, some of the insects are killed but some of them live, and you need to look at the F-1s and what happens to them; and we haven't been able to collect that kind of data yet. Also the very understanding that the populations vary at all and that the spraying might affect them from generation to generation is relatively new for forest insects, although, it certainly isn't for agricultural insects. But forest insects -- a lot of the things that are old hat in agriculture are just beginning to be recognized as true possibly for forest insects.

QUESTION (J.M. Herbers): I'd like to ask first a couple of very general questions, for those of us who are not up on insect toxicology. Can you tell us a little bit about the compound carbaryl itself -- how does it work, is it a neurotoxin, is it a chlorinated methane derivative or ?

RESPONSE (J.L. Robertson): It is one of the carbamates. It is a neurotoxin.

QUESTION (J.M. Herbers): Then why isn't it toxic to vertebrates? If it is a neurotoxin, those are generally broad spectrum.

RESPONSE (J.L. Robertson): Well, it is, but you have to ...

QUESTION (J.M. Herbers): Relative to DDT it's not?

RESPONSE (J.L. Robertson): Well relative to DDT it is toxic to mammals. Relative to other chemicals available it is not. Its got a methol group in it which somehow or another makes it safer.

QUESTION (J.M. Herbers): Is much known about how the insects actually do detoxify it?

RESPONSE (J.L. Robertson): A lot is known about some insects, like houseflies.

QUESTION (J.M. Herbers): But experience shows that insects in different orders and in different families can have very different mechanisms.

RESPONSE (J.L. Robertson): Right and nobody has looked at the detoxification, for example, in the budworm.

QUESTION (J.M. Herbers): If you don't mind, I would like to ask you quite a few questions about the genetics because I am a population geneticist myself. You've shown quite clearly that there is an enormous amount of variation among spruce budworm species, especially in the western part of the country; and also variation between species with respect to LD50s for carbaryl, and I was wondering if you've yet got enough data to start to partition the variance into between species, within species, between populations, within populations, and so forth. Because that I think is a really critical question -- where is the variance? Is most of it between populations, is most of it within populations and so forth.

RESPONSE (J.L. Robertson): I think we have a good basis to say most of it is within populations.

QUESTION (J.M. Herbers): But the point of your talk is that there is a lot of variance between population, as well.

RESPONSE (J.L. Robertson): Right, we think most of the variance occurs within a population.

QUESTION (J.M. Herbers): Doesn't that present problems, though, for your implication that resistance is related to previous spraying with something like DDT? If most of the variance is within populations, presumably individuals within a population have had similar histories, genomes have had similar histories, and so most of the variance should therefore be between populations rather than within. If the pesticide cross linkage is really important.

RESPONSE (M.W. Stock): Very good questions. All I can say is there is a lot we don't know yet. And the other thing is what constitutes a population. It is very ill-defined. Also, how much do these insects move from one place to another? Dispersal is a whole topic that is being researched for budworms and tussock moths and we don't really know how far they move. So even talking about what is a population is very nebulous right now. We've done... one of my graduate students ... comparative genetic study of all the species of Choristoneura and they are extremely homogenous, genetically at least, by isozyme work. They vary a lot in their response to chemicals, but in their general genetic relationship they are all very similar.

QUESTION (J.M. Herbers): Well along the same line, you mention in your paper that you've done quite a bit of lab work as well, which I think is really important as well as the field work -- and these bugs are reasonably easy to culture, is that right?

RESPONSE (J.L. Robertson): No, we're just good. They are not easy to culture.

QUESTION (J.M. Herbers): That blows the next question. I was just going to ask if you have yet started to perform selection experiments in the laboratory.

RESPONSE (J.L. Robertson): Okay, what we have done ... I should give a rundown on the lab colonies that we have. In 1967 we established a huge western

spruce budworm colony in Berkeley that we were able to raise without diapause, which meant that it was available year-long, instead of having to put them in the refrigerator for four months. We have them available continuously. We have that as basically the baseline culture. Last year we established four other colonies from some of the population sites that I was discussing; and what we are planning to do when we get the colonies to sufficient size is to work on these problems more. Unfortunately, it takes about a year and a half to two years to get the colony built up to that level. Because we are not talking about tests that use 10-15 animals, we're talking about 500-1000 for each experiment.

QUESTION (H.M. Herbers): I can appreciate the difficulty because I work with an organism that has to go through a six month diapause and it is really a drag. Okay, well I'd like just one more question about the genetics, if you don't mind. It seems to me really critical in understanding resistance in natural populations, to understand whether that resistance comes about as an evolutionary response to a selection pressure, or whether that resistance is a result of some genes being turned on in the population. My understanding is that so far the available literature just cannot differentiate between those two. Can you suggest any way to approach this issue, obviously you have to do selection experiments in the laboratory and estimate heritability and so forth; but the whole issue of the physiological basis of resistance is that big black box still for many, many species.

RESPONSE (J.L. Robertson): I don't know yet, I have to wait and see what we get from the selection experiments. This whole thing has just been a step by step process.

(M.W. Stock): Interesting that you should bring that subject up. Last week I talked on bark beetles at a meeting in Banff and what we found is that when you stress the population, you get greater genetic diversity. There if a certain amount of theory that says if you stress a population you get less genetic diversity. We

very clearly get more genetic diversity. It was a very interesting discussion, everybody got talking about why this would be so. We may try to test the bark beetles by stressing them and trying to differentiate in that way. Trying to figure out why, when you select and you kill off lots of them, when you put them under great stress you get greater diversity because the remainder hasn't much of a greater chance to diversify. It was a very big revelation, at first I thought it must be an artifact of collection. We did it wrong -- that's your first reaction, but then you realize that it is so consistent that you can't just say, because it doesn't fit with what you thought, that you did it wrong. So that is a thing we are testing now.

QUESTION (J.M. Herbers): Well that work is really very interesting and I applaud you for doing the hard work, I know it is hard work. My final question relates more to policy issues. Your work clearly shows that since there is variation within populations and between populations, that EPA registration procedures are just plain wrong. Now, can you suggest what the real implications are going to be for registering pesticides and testing them from your work?

RESPONSE (J.L. Robertson): You get caught between the bureaucracy you work for and science. I don't know what we're going to do besides diligently publishing our information. We present it whenever we can, and I guess basically we are trying to make enough people pay attention to what we are saying so that, hopefully, eventually the message will get through to people making the policies.

QUESTION (J.M. Herbers): Presumably your work is being funded by those same people who make policies.

RESPONSE (J.L. Robertson): No. I might relate a little story that sort of explains this. In 1971, I had spent I guess 5 years testing 25-30 chemicals against Douglas fir tussock moth as alternatives to DDT. When it came down to the issue of the emergency, the alleged emergency in Oregon, that year -- our project suggested five alternatives to DDT. Guess which chemical got sprayed? DDT! All you can do is present your data.

QUESTION (J.M. Herbers): Well, good luck to you. Thank you.

QUESTION (B.S. Burns): Your slides make me glad I haven't seen a gypsy moth caterpillar in a couple of years -- turns out they are even uglier when you look at them under a microscope, have to meet them face to face. So, I'm glad about that, but a couple of years ago, like everyone else in Vermont, we did have a real gypsy moth problem and I guess about half the oak stands in this state were defoliated. One thing that always struck me that about this virus is that when we got to an area where the moth population was collapsing and all the foliage had been chewed, the bugs were halfway through their development and the larvae that were left all had the wilt disease. I would report that they died from starvation and wilt. My question is, which are they dying from? Perhaps it is the same thing -- the starvation leads to wilt disease. But is there a way to say the caterpillars are dying from one or dying from the other?

RESPONSE (K.S. Shields): Well, a few years ago we did a study analyzing the causes of collapse in natural populations and the important disease agents in natural populations. Essentially we did necropsies on the insects and we determined that the nucleopolyhedrosis virus was the most important microbiological agent operating in various kinds of gypsy moth populations, sparse and dense. But, of course, that doesn't account for factors like starvation. There really isn't any way to determine when there are many factors involved, which one is the most important after the insect is dead. This all goes into the whole disease complex and the epizootiology model and population prediction. As Mollie mentioned, models start out with very simplistic kinds of schemes and then you test them. Well, we're really in the very, very infancy of testing ours. We really don't even have a model. We are in the process of assembling one, and starvation could be one factor.

QUESTION (B.S. Burns): If you are going to be using virus though it seems as if it would be helpful to know if you should apply it early in the build up of the insect -- like BT (the bacterial insecticide). Is it best to use it before the insects are too numerous, or is it better to use it later when the insect is already stressed by the

starvation? When would virus be most effective in terms of the population build up if it were applied as an insecticide?

RESPONSE (K.S. Shields): Well, it depends on how you are going to introduce it into the population. If you are talking about aerial spray, the recommended application now is two doses, and you spray first when they are second instars. The reason for that is, if you spray too early when the insects are first hatching, they are not up in the canopy, they don't eat enough, so even though you can cover the foliage with inclusion bodies the odds of one very small first instar larvae ingesting a lethal dose of inclusion body are not great enough to justify spraying. If you wait too long, the virus still kills them, but the dosage goes up with the insect's body weight. The larger the insect the more it takes to kill it. So it's a compromise -- second instars are probably the best stage to hit in an aerial application, but in alternate application methods that is a whole different story.

QUESTION (B.S. Burns): Another question -- we always say a virus would be a great pesticide if it affected only gypsy moths and not the other insects, not the other creatures around; but I have a feeling if we ever got to doing this operation, if we were spraying it over houses, people would get concerned and think it was going to mutate, and what about the next andromeda strain, and all this. Are we really sure this thing can't mutate and become a bug that is a little more infective?

RESPONSE (K.S. Shields): No, of course not. You are never really sure. GYPCHK was in safety testing for many years before EPA registered it. It has been tested against many, many species of invertebrates and vertebrates; it has been injected into brains of mammals, it has been through all sorts of extensive testing. But the most that we can say is that all evidence indicates that it is environmentally safe, that it is not infectious in any other species, and it is monitored. But that is something that will have to be looked at over the years as the organism is produced, if a commercial producer is making it. It will be important to monitor any microorganism to make sure that it has not mutated. This really isn't being done now.

QUESTION (B.S. Burns): Are the registration regulations more strict for microbials than chemicals because of this possibility of mutation:

RESPONSE (K.S. Shields): I really can't answer that because I am not familiar with the procedures for chemicals. Perhaps Jackie could -

(J.L. Robertson): I think that they are about the same.

(M.W. Stock): I would like to make just one point -- and that is, from a genetic point of view and from just a biological point of view, insects cycle naturally and deciding what is killing them is very difficult as we have been discussing here. At some point in time, the populations will decline naturally; Douglas fir tussock moth is very predictable in that way. So, if you spray at the right time you get very high mortality, whether it is caused by the spray or whether they were going to die anyway. So, causal relationships are very difficult to identify.

QUESTION (B.S. Burns): If we have to give communities and landowners, and so forth, advice on whether to spray and make that rather substantial investment on a piece of real estate, it would be nice not to ask people to spray if their population is going to collapse this year.

RESPONSE (M.W. Stock): Right. On the other hand if you tell them to spray then they say you gave them such wonderful advice because they all died. That is the politics of it, you see.

QUESTION (B.S. Burns): Okay, this is just a curiosity more than anything. I haven't been keeping up with my Mother Earth News or whatever it is, but I know they probably all say that you can macerate gypsy moth larvae and spray them on the trees and you can make your own virus insecticide yourself. Would that work: I mean if a homeowner asked me can I take a bunch of dead gypsy moth caterpillars and mash them up and spray them on the trees?

RESPONSE (K.S. Shields): Well, I hate to tell you what GYPCHEK is made of. That is what it is. Now, viruses of course have to be grown on living cells

and there are two ways of producing baculoviruses, and the best way is to produce them in vitro, in cell culture. This has been attempted with gypsy moth virus, but it has not been economically feasible. There haven't been any gypsy moth cell lines that have been productive enough to justify the investment in them. So, some time ago the decision was made to produce it in vivo. So, we infect insects and shortly before they die - when they have maximum number of inclusion bodies - they are frozen and lyophilized. They are put through a mill which breaks off most of the setae which cause the allergenic reactions; and then they are ground up. And that is GYPCHEK. It is insect body parts and polyhedral inclusion bodies. Now this material is tested for presence of pathogenic microorganisms and this is the major problem with growing viruses in vivo. You have allergenic material from the insect parts and you have contaminated microorganisms. We further purify it for laboratory use, the pictures that I showed you of the inclusion bodies were highly purified; but it is much too expensive to do that for a spray operation. So GYPCHEK was registered as ground up insects. So, yes, it would work.

QUESTION (K.Carter): Barbara, I can see a lot of eager people out there who want to ask their own questions, so I'm not going to take too long. But there are a couple of things that came to mind while you were speaking that I just can't pass up the opportunity to talk about. I think that your study with the black walnut and the ambrosia beetles was an excellent example of the need to study the biological system, both of the insect and of the host over a long period of time in order to be sure that you have got all the implications before formulating a strategy. I just wonder if you feel that the biology of the trees has been followed sufficiently long to be able to predict whether these sprouts from the stumps will be of the same quality as the seedlings; because I know frequently it is the case, especially with sprouts from older stumps, that you expect poorer form or more susceptibility to heart rot, etc., from stump sprouts as opposed to seedlings.

RESPONSE (B.C. Weber): The same is true for black walnut trees. In my study we haven't followed the trees long enough to know if quality is affected in the

future for these trees. I also don't know if that very fast growth rate is going to continue over the life of the trees; they may slow down again later on and in fact maybe go back to the slower growth rate or become susceptible again. But for a short period of time, within a few years after attack, the trees are better and the sprouts that do come up are usually very straight and very fast growing -- so they look good initially.

QUESTION (K. Carter): When you speak about them being faster growing -- that would be an annual growth rate. They do eventually catch up to where they would have been had they not been killed back to the ground at some point?

RESPONSE (B.C. Weber): I would say it would depend on the age at which the trees were attacked. If the trees are at age 4 in the example that I gave, I would say that the sprouts would catch up, because the sprouts are growing at the rate of maybe 5 feet a year and the trees would maybe be 7 feet tall for the average of the plantation. So, within 2-3 years the sprouts are going to be as tall or maybe even a little bit taller than the average tree.

QUESTION (K. Carter): I can tell there are a lot of geneticists on the panel this morning, because I am one too. I just have to give you or maybe one of the other speakers, too, would like to comment on the very long term effects of interactions between insects and forest trees on the genetics of the tree populations -- and maybe talk a little bit about long-term co-evolution of the insects and their hosts. Would you like to do that?

RESPONSE (B.C. Weber): I am not a geneticist, so I am going to beg off a little bit on that one; except to say that with my study on the ambrosia beetle, the black walnut trees that I studied were from different seed sources -- which means they had different genetic backgrounds. So I looked at this particular factor to see if the ambrosia beetles were affecting particular trees and then looked at the long term response of the trees after attack. What I found was that yes, there were differences among the different seed sources in which trees

were attacked. I also found that the seed sources which were most heavily attacked were also the seed sources that recovered the best. Now, another thing, and this may be a coincidence, but the seed sources that were most heavily attacked and that recovered the best were also seed sources in areas where the ambrosia beetle occurs now. The seed sources that were attacked but did not recover very well are in places where the beetle is not presently found. This insect is an introduced insect into the country. It was introduced in the early 1930's. Now I don't think the insect has been around long enough to put any kind of evolutionary pressure on the trees to affect the fact that some trees are resistant and not resistant. I think it may be just an artifact of the population, but some of the differences were significant. If somebody else wants to talk about the co-evolutionary aspects, I defer to them.

RESPONSE (M.W. Stock): At this meeting that I recently attended, another thing they found was that if you take -- say -- Douglas fir and you put spruce budworms from the same area on it there is less damage than if you mix them from different areas say, from 100 miles apart. So that the adaptation certainly goes both ways. You get most damage if you take a population of budworm and a population of Douglas fir from two different areas. So, there are really very high levels of co-evolution. That was the whole subject of that meeting -- it was quite fascinating. The other thing is that in bark beetles, some of the controversy -- there is a fair amount of controversy about how to manage bark beetles, you can't spray very effectively since they whip out of one tree and whip into another one so fast they aren't exposed -- but one of the management techniques involves cutting down vigorous trees that the beetles might be likely to attack. This is, over a period of time, not really terrific for the stand. That is a very interesting subject for discussion, and as I say we recently spent two days on it and just barely scratched the surface of some of these questions. Mostly we raised questions -- like here. You don't answer a whole lot but you recognize the questions exist.

QUESTIONS FROM THE AUDIENCE:

COMMENT (A.M.Carey): Because E.P.A.'s Office of Pesticide Programs payed my way here, I feel I should mention a couple of things in terms of how pesticides are registered under the Federal Insecticide, Fungicide, and Rodenticide Act, and how this is administered by E.P. A. You have to keep in mind that E.P. A. is required to register a whole spectrum of pesticides. In order to do that, we had to set up a series of registration guidelines you can hand out to any potential manufacturer -- of anti-fouling paints, slimicides for paper mills, saniflush, and baculoviruses -- so the guidelines don't seem to be very specific to this particular use of a chemical or a microbial agent. The guidelines had to be written "generically". Secondly, you have to keep in mind that forestry uses of pesticides are considered by E.P.A. to be a minor use compared to the agricultural uses. The Forest Service has done a very good service by conducting the additional work to allow this particular kind of agent to be registered for forestry uses because it is really not worth it for a chemical company who must answer to stockholders to go ahead with the research that is required. It is not cost-effective for them. The Forest Service has done this and thus certain agents have been registered for forestry uses. We have to keep this in mind when speaking of impact on E.P.A. registration standards. It's not that simple.

QUESTION (S.V.Kossuth): I have a question for Mollie. What I would like to know is have you looked at the stages of development of the insect in relation to when they are most susceptible to the various strains?

RESPONSE (M.W. Stock): That's a question that was brought up during coffee break. The instars, the different larval stages, vary in their susceptibility to different chemicals and not just a linear fashion. There are no gross changes in the esterases during larval development. We've seen changes, great switches, between, say, when pupation occurs. That is certainly something that would be worth looking at. We have not compared the instars in great detail. But with the instars that we have compared, say second, third,

fourth and fifth instars, there are no changes. No obvious changes in frequency at least, but there are other things that need to be looked at. That is a good possibility especially with acephate, which is directly related; the esterases are directly related to metabolism of acetate.

QUESTION (C.J. Wang): Do microbials associated with insects affect their response to chemicals?

RESPONSE (J.L. Robertson): Certainly a possibility but, unfortunately, when you run a bioassay for a chemical all you have got are your controls, and the question is did they live or did they die? So, we don't know.

RESPONSE (M.W. Stock): Back to bark beetles. When a bark beetle attacks, there is a very close relationship between the fungus, the various fungi, that are carried by a bark beetle, and whether or not it kills the tree. There is a very close relationship which is essential in understanding the tree mortality and the relationships between them. I think that's a very good question -- something we don't know a whole lot about, but more is being learned all the time. I think we know more about it -- maybe I'm wrong, but I think we know more about it in the bark beetle-tree relationship, than we do in budworms and the defoliators.

QUESTION (R.S. Kelley): A question for Kathy. Is there any evidence to suggest a direct carry-over of a sub-lethal dose of virus within the insect from one generation to the next?

RESPONSE (K.S. Shields): There is no evidence at present. Some of this work is being done now -- working with sublethal doses, looking for chronic infections - evidence of chronic infections, transviral transmission -- all this area. To my knowledge no one has produced any positive evidence of this occurring. There is a lot of negative evidence, but the fact that you can't find it doesn't mean it's not there. There is another whole area that really hasn't been investigated and that is the area of viral latency. For many, many years a lot of people have suspected that gypsy moth virus may be operating in some kind of a latent form that could be triggered by different

stress agents, but we really don't know about that. It is not an easy area to study. It's not an inexpensive area to study either. So we really don't know that, but all evidence so far on low dose levels that I am aware of is negative. One theory that is being proposed now for many of the baculoviruses is sort of the single bullet theory -- that it takes one viral particle to infect an insect and if that one viral particle invades the cell and replicates that insect is a dead insect. The dose response is just the odds of getting that one viral particle in an infectious form into a cell. Now this is just a theory, but evidence is being accumulated that supports this theory.

QUESTION (R.S. Kelley): My second question related to the break-down of virus by ultraviolet radiation. What do you know about survivability of the virus on the egg mass?

RESPONSE (K.S. Shields): Well, the testing programs that are being done now would spray egg masses shortly before hatch. If this is going to be used as a home owner kind of technique, people would be advised to go out in the middle of April and spray their egg masses, just shortly before the insects are due to hatch so that it wouldn't be exposed for that long a period of time. Also, there is difference in virus preparations. The virus that is liberated from a dead insect is incorporated with all of the insect body parts -- all this proteinaceous matter -- and this virus seems to be more protected from ultraviolet radiation than purified preparations. We did virus persistence studies as part of the E.P.A. registration package. We went out into natural populations that had never been treated with virus, but that had had natural virus incidence in the past years. We went out in the spring before the insects hatched and collected bark samples, soil samples, litter samples and some lethal doses of virus in these samples, as tested by bioassay. So when it's protected from UV either by a formulation or by the insect body fluids, or the fact that it is just not exposed to light because it is down in the crevices of the bark, it is quite resistant. Egg

masses are covered with many, many layers of setae that the female deposits on the eggs. If you take an egg mass to a laboratory and just squirt it with virus -- just plaster it and put it under the scanning scope, the first time I did that I was positively horrified because I put it under there and I couldn't find any virus. Yet I knew I had just loaded this thing up with it. Well, it soaks down in to the layers of the setae, and when you spray an egg mass you can find inclusion bodies right on the surface of the eggs, below many, many layers of the setae. So they probably would be more protected in that fashion and may go from one generation to the next.

QUESTION (R.S. Kelley): Where do you find your greatest number of lethal doses?

RESPONSE (K.S. Shields): There were differences in samples -- I really can't remember the specifics of the data. The bark was very variable and we assumed that it probably depended on whether an insect had died on that particular piece of bark or not. We had one little sample that was half the size of a dime, scraped off the crotch of a maple tree, from one plot that had never been sprayed with virus; this was supposed to be the pre-spray sample. It wiped out every insect. You know, LD100 on everything. We couldn't dilute it down enough. There were probably a half a dozen larvae that died right in that little spot. So that was really high, other samples were minimum or none at all.

QUESTION (M.Morselli): Is there any indication of the virus having an effect on the tree?

RESPONSE (K.S. Shields): No, we have no indication of that. In the environment, if viral particles are present they will not be viable for very long. Viral particles are wiped out very, very readily by ultraviolet light -- or by desiccation, or many other things. They are not very stable at all. The inclusion body is much more stable, but the inclusion body has to be dissolved in order for virus to gain entry into any tissue. The inclusion bodies are very, very stable; except at high pH; the reason that inclusion bodies dissolve in lepidoptera larvae is primarily because of the gut pH. Once the inclusion bodies dissolve,

then the viral particles have to enter cells. We really don't know very much about what determines the host range of a virus. This virus won't replicate in anything except gypsy moth. We really don't know what determines the host range of a virus; we strongly suspect it may be something like these protein structures on the viral envelope that could act as sort of a lock and key mechanism to gain entry into a cell. You can dissolve the inclusion bodies, but that doesn't mean anything. The virus has to gain entry into a cell, it has to gain entry into the nucleus, it has to be able to uncoat its DNA and start its replication process. So the fact is that baculoviruses have the most restricted host range of any of the viruses. They are the only virus group that has no counterpart at all in either plants or vertebrates. It is very, very unlikely that a baculovirus could have any mode of action in something as different from a gypsy moth as an oak tree is.

QUESTION: I would like to ask Barbara how the Xylosandrus is killing the tree and if there are preventative measures.

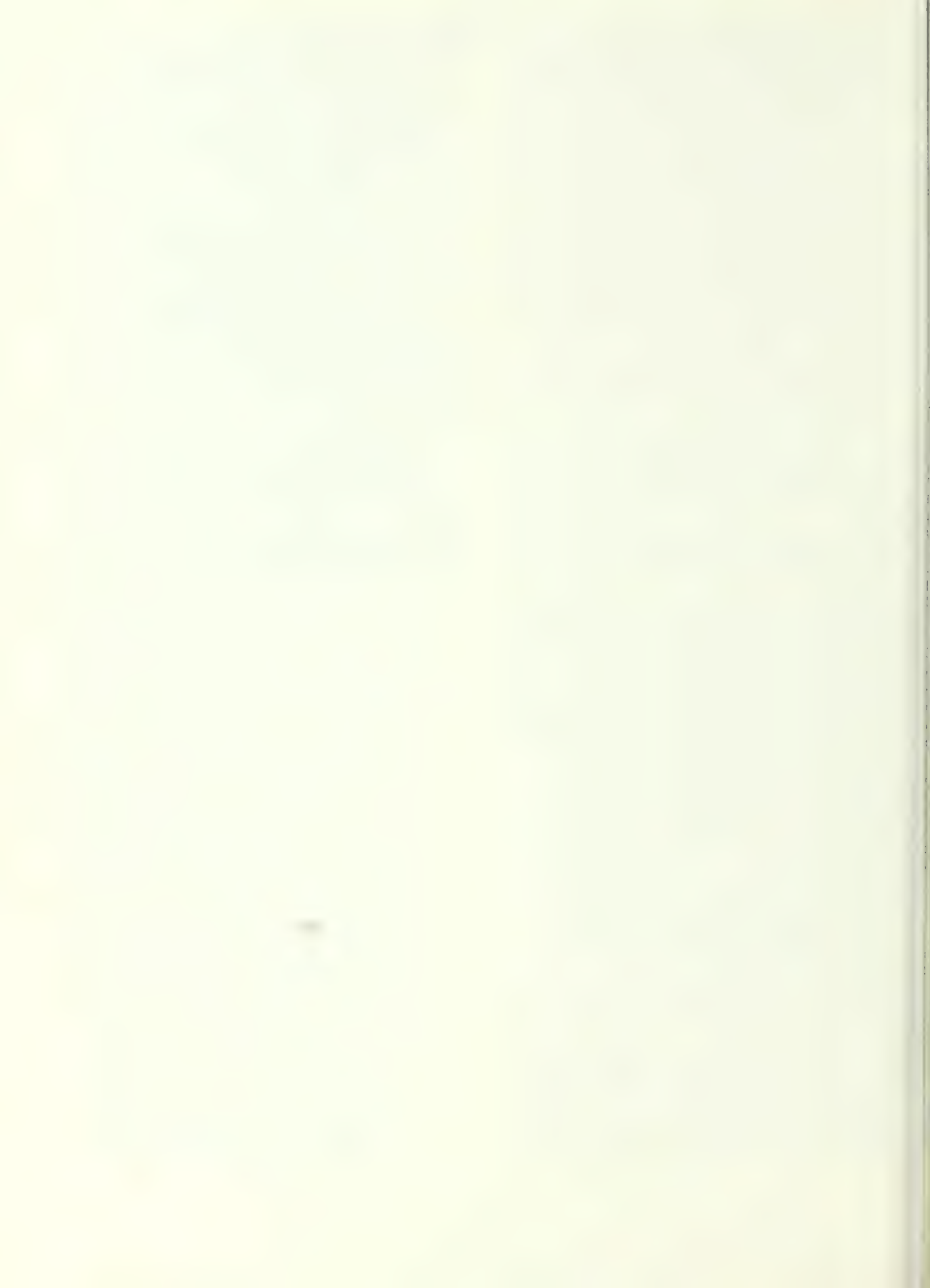
RESPONSE (B.C. Weber): Xylosandrus germanus is an ambrosia beetle; that means it is related to bark beetles and therefore it carries a fungus that it uses as its nourishment when it is growing inside the tree. My hypothesis is that it is carrying other fungi into the tree that cause the wilting and the dieback of the tree. So it is an interaction between the beetle, some fungus or fungi or other microorganism, and the tree itself that actually causing the dieback. To speculate on some preventive measure -- that one is difficult because you would have to figure out which of the three agents is the more important cause and then work on that one to prevent it. Right now we don't know enough about them all to speculate very far; so I'm going to hedge on that one.

QUESTION: Is it a bark infection in the lower part of the tree?

RESPONSE (B.C. Weber): It occurs in the lower part of the tree and the beetle tunnels all the way into the wood, sometimes all the way into the pith; so its not just in the bark area.

QUESTION (B.C. Weber): I have a question for Kathy. My question is -- she talked about the larvae that were parasitized by the fly; and then later being affected by the virus also. My question has to do with the long term affects on the fly populations. Aren't the parasites being killed in the virus-infected larvae?

RESPONSE (K.S. Shields: Yes, that's exactly true. We're looking at it more from the aspect of population prediction. It is true that if you were going to use Blepharipa as a vector of virus, the virus mortality will increase and the Blepharipa population will decrease. So that depends on whether you are interested in parasites or gypsy moths; and most people just want gypsy moths dead, they don't really care how it gets killed. But, the aspect that is interesting about it is if you are trying to assess populations from one year to the next -- if Blepharipa is operating in the gypsy moth population, its a pretty good bet that gypsy moth population is going to have Blepharipa. We are not sure of that but the laboratory evidence exists.



DISPLACEMENT: ONE CONSEQUENCE OF NOT MEETING PEOPLE'S NEEDS¹

Dorothy H. Anderson²

Abstract.--Defines displacement from a recreation researcher's viewpoint and illustrates it with findings from a study of use within the Boundary Waters Canoe Area Wilderness. Findings show that displacement is likely to be caused by litter, noise, overuse, and encounters with others. In many cases, the causes of displacement can be managerially controlled.

Forest managers seek to manage recreation resources to provide people with opportunities to meet their recreation needs. But because recreation use continues to change, some people's needs are not met. Failure, for whatever reasons, to meet people's needs often increases visitor conflicts, visitor displacement, and visitor dissatisfaction.

The purpose of this paper is to help nonrecreation natural resource professionals understand what happens when some people fail to have their recreation needs met. The paper will focus on visitor displacement, one consequence of failing to meet recreation users' needs. Specific intents of the paper are to define and briefly discuss displacement and to provide a context for examining the displacement phenomenon in recreation environments. Selected findings and management implications from a study of recreation displacement are presented to illustrate the phenomenon.

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DEFINING DISPLACEMENT

In the social sciences, geographers and sociologists often refer to displacement as free-compelled or forced migration brought about by political forces or government actions (Burdge and Ludtke 1973, Muller 1976). Displacement, then, refers to involuntary movement from one place to another and generally precludes a return to the original location (Shields, M. 1975). To illustrate this meaning, suppose an individual lives in the path of a proposed roadway. If plans for the roadway are approved, the individual is forced to move but is free to choose where to move.

In recreation research we have taken the geographer's and sociologist's definition of displacement and have extended it to include the social psychologist's viewpoint. Adding this viewpoint allows us to examine movement as specific kinds of changes in an individual's behavior. We recreation researchers define displacement as the outcome of a decision to change behavior--an outcome caused by adverse changes in the recreation environment. In addition, displacement can be either on-site or off-site and it can refer to either spatial or temporal changes people make in their recreation behavior (Anderson 1980). On-site displacement is the outcome of a decision to change behavior within a recreation area; off-site displacement is the outcome of a decision to leave a recreation area altogether. Off-site displacement always reflects a spatial change

in behavior, but on-site displacement may reflect a spatial as well as temporal change in an individual's behavior. For example, people who have been displaced on-site may hike different trails, camp at different sites, and enter a recreation area through different access points. Any of these behaviors reflect spatial changes. An example of a temporal change could be people who decide to enter a recreation area through the same access point but at a different time of the day, week, month, or year. Once in the area they use the area in the same way as they have in the past.

According to our definition, displacement is caused by adverse changes in the recreation environment. An adverse change is simply a change the recreation user does not like. These changes are classified as social, environmental, or managerial. An example of an adverse social change might be an increase in the number and kind of users to a recreation area. Increases in use often lead to greater pressures and competition for space among recreation users (Lucas 1964, Knopp and Tyger 1973, Schreyer and Nielson 1978).

Environmental changes can be vegetation or landscape changes brought about by natural or human forces. Fires, floods, insect infestations, and mining and timber practices can alter the landscape significantly and sometimes make it less desirable for recreation use. For example, in some parts of Pennsylvania, recreation use has decreased as populations of gypsy moths have increased. Many recreation users, not desiring to recreate in areas heavily infested with these insects, have been forced to recreate in other areas where gypsy moths have not yet invaded (Shields, K. 1983).

Displacement can also result from managerial changes stemming from new directives, policies, and legislation. For instance, increases in the number of users to some federal lands have prompted land managers to allocate use through various rationing schemes. Some recreation users are displaced from these areas because they do not want the bother of applying for admittance to the area. Other users are more directly displaced when their applications for admittance are denied because entry quotas are filled.

MODELING DISPLACEMENT

Because displacement is defined as a change in an individual's behavior, it can be modeled in an attitude-behavior context. An individual's intent to behave a particular

way depends on the individual's attitude toward behaving that way. Symbolically we can show that attitudes are composed of beliefs and evaluations of beliefs (Fishbein and Ajzen 1975):

$$A_B = \sum_{i=1}^n b_i e_i$$

where, A_B is an attitude toward performing a behavior,

b is a belief about the consequences of performing a behavior, and

e is an evaluation of the favorableness or unfavorableness of performing a behavior.

Combined, beliefs and evaluations measure an individual's attitude toward performing a behavior. Thus two people in the same environment may behave differently because their beliefs differ, their evaluations differ, or their beliefs and evaluations differ.

The following example uses this model to illustrate displacement in a recreation context. Two anglers who have fished a particular river in the past are considering fishing it again. Since the time of their last fishing trip on the river, a canoe rental business has begun operating about a mile upstream of their favorite fishing spot. The first angler believes that the canoe traffic generated by the rental business will markedly decrease the opportunity to catch fish. Because catching fish is this angler's most important reason for using the river, not catching fish will strongly diminish the first angler's recreation experience. Based on this belief and evaluation, the first angler decides not to return to the river and fish. Catching fish is also the second angler's most important reason for using the river and not catching fish would strongly diminish this angler's recreation experience. However, unlike the first angler, the second angler does not believe that the canoe traffic will decrease the chance to catch fish and decides to return to the river to fish. Although both anglers share the same evaluation for catching fish, their beliefs differ. Therefore, their attitudes and consequently their intentions differ toward fishing from that particular place along the river. The first angler has been displaced because the decision to fish elsewhere (i.e. change behavior) was made in response to an adverse change in the recreation environment (i.e., canoe traffic). In contrast the second angler has not been displaced.

SELECTED FINDINGS FROM A STUDY OF DISPLACEMENT³

We conducted a study in the Boundary Waters Canoe Area Wilderness of northeastern Minnesota's Superior National Forest to find out if evidence of displacement exists, and so, to identify the likely causes of displacement. The Boundary Waters, encompassing more than one million acres of land and water, is the only lake-land wilderness in the United States.

Methods

Every group entering the Boundary Waters is required to have a permit, and copies of the permits are retained at the Supervisor's Office of the Superior National Forest. We drew a sample of 1,016 names from permits issued between Memorial Day and Labor Day in 1978 and in 1979. A questionnaire was mailed to each permittee included in the sample. Nearly 85 percent of the users surveyed returned the questionnaires.

Because we were interested only in on-site displacement within the Boundary Waters, we needed to look at people who had used the Boundary Waters several times. Therefore, people who had made fewer than five trips to the area were excluded from our study. After eliminating these people, 619 questionnaires remained.

We measured changes in behavior with the following questions:

- a) On your recent visits to the Boundary Waters did you enter through different entry points than you did on your early visits?
- b) On your recent visits to the Boundary Waters did you select campsites differently than you did on your early visits? and,
- c) On your recent visits to the Boundary Waters did you enter on a different day of the week than you did on early visits?

We defined early visits as the first half of the total number of visits made to the Boundary Waters and recent visits as the last half of the total number of visits made.

³Much of the material in this section has been excerpted from an earlier paper. See Anderson, D. H. and Brown, P. J. forthcoming issue of Journal of Leisure Research.

Respondents could answer either "yes, at least some of the time" or "no, never" to each question. For those answering yes, we measured their attitudes toward selected outcomes of the use changes.⁴

Beliefs about the outcomes of each use change were measured by asking respondents how likely each outcome would be if they did not change behavior. For example, those users who changed entry points were asked to:

Think back to your early visits to the Boundary Waters. Pick an entry point that you used on early visits but not on recent visits. Write the name of that entry point in the space provided. If you were to use that entry point now, how likely do you think each of the following would be?

Users who selected campsites differently or entered on a different day were asked similar appropriately worded questions. A 7-point Likert scale, ranging from "not at all likely" (scale value = 0) to "very likely" (scale value = 6), was used to measure the strength of the users' beliefs about each outcome. Evaluations of outcomes were measured by asking users how much each outcome, associated with a use change, added to or detracted from the users' recreation experience. A 7-point Likert scale, ranging from strongly detracts (scale value = -3) to strongly adds (scale value = +3), was used to assess the strength of user evaluations. Belief scores and evaluation scores for each outcome were multiplied to develop attitude scores.

By our definition, displacement occurs when users change their behavior in response to adverse changes in the recreation setting. Users' perceptions of adverse social changes were identified through negative attitude scores. For example, a user may no longer use an entry point that was used frequently in the past because the user believes that if this entry point were used, contacts with noisy people would be 'very likely'. Moreover, these contacts 'strongly detract' from the user's recreation experience. This user's belief score would be 6 and the evaluation score would be -3, yielding an attitude score of -18.

Behavior changes

More than 70 percent of the 619 respondents surveyed changed their use of the

⁴Attitude measurements were not made for those answering "no, never."

TABLE 1

Belief and Evaluation Scores for Selected Outcomes

Outcomes Related to Changing Entry Points		Outcomes Related to Changing Campsites		Outcomes Related to Changing Entry Days				
Belief ^a Scores	Eval. ^b Scores	Belief ^a Scores	Eval. ^b Scores	Belief ^a Scores	Eval. ^b Scores			
See litter along portages	4.04	-2.70	Find litter in the campsite area	3.30	-2.63	Come into contact with noisy people	4.04	-2.64
Come in contact with noisy people	4.00	-2.62	See peeled birch trees	3.16	-2.62	Camp within hearing distance of others'		
See litter along the shore	3.47	-2.70	Camp at heavily used campsites	2.73	-2.12	campsites	3.71	-2.32
See worn-out campsites	4.14	-2.08	Camp within hearing distance of others'			See large groups	4.33	-1.91
See large groups	4.50	-1.92	campsites	2.25	-2.34	Camp at heavily used campsites	3.83	-2.11
See motorboats	3.70	-1.97	Camp at sites easily seen from			See motorboats	3.86	-1.96
See worn-out portages	3.98	-1.79	others' campsites	2.71	-2.02	Camp at sites easily seen from others'	3.82	-1.93
See organizational groups	4.34	-1.59	See tents of others from your campsite	2.82	-1.98	campsites		
See other people at entry points	5.20	-1.17	See watercraft pass by my campsite	3.76	-1.42	See organizational groups	4.40	-1.57
See people on portages	4.74	-1.18	Camp close to hiking trails	1.78	-1.02	See other people at entry points	4.84	-1.18
See canoes	5.27	-0.68				See other people on portages	4.66	-1.15
						See canoes	5.00	-0.73

^aBelief scores were obtained by averaging scores across all respondents. Beliefs could range from 0.00 (not at all likely) to 6.00 (very likely).

^bEvaluation scores were obtained by averaging scores across all respondents. Evaluations could range from -3.00 (strongly disagree) to +3.00 (strongly agree).

Boundary Waters over time. Eighty-four percent (n=513) of these people used different entry points on recent trips compared to early trips. Seventy-five percent (n=454) of the respondents selected campsites differently and 73 percent (n=438) entered the Boundary Waters on a different day of the week.

Beliefs and evaluations of beliefs

Belief and evaluation scores are shown in Table 1 for outcomes associated with selecting entry points, campsites, and a day to enter the Boundary Waters. The scores were averaged across respondents. Belief scores greater than 3.00 are evidence that respondents believed the outcomes associated with one of the three changes were likely. Scores less than 3.00 indicate that outcomes associated with a behavior change were unlikely to occur. Evaluation scores greater than zero represent outcomes that are perceived as adding to the respondents' recreation experiences. And, outcomes perceived as detracting from experiences have score values of less than zero. None of the outcomes we report here added to the users' experience.

Changes that respondents made in entry points and entry day show that respondents believed that if they behaved as in the past, then the outcomes listed were likely and could detract from their experiences. According to means for outcomes related to campsite selection, respondents believed that if early behaviors were followed most of these outcomes would be somewhat unlikely but any one of these outcomes would detract from their recreation experiences.

Attitudes

We combined belief and evaluation scores to determine respondents' attitudes toward each outcome associated with a behavior change (Table 2). Individual attitude scores were averaged across respondents to produce aggregate attitude scores.

Litter, noise, and overuse (i.e., seeing worn-out campsites and portages, camping at heavily used sites) were perceived more negatively than seeing other people. This finding was true for all three kinds of behavior changes considered. Also, fewer users perceived visual encounters with others as negative outcomes, than those who perceived litter, noise, and overuse as negative outcomes. The most striking implication of these findings is that displacement is likely to be caused by more than visual encounters with others. An additional implication is that encounters with others may not be as

important in displacing users as other reasons.

MANAGEMENT IMPLICATIONS

We believe that the outcomes we identified as related to displacement can be managerially manipulated. Our study documents that change, and possibly displacement, is taking place within the Boundary Waters and that this change is at least partly due to adverse environmental and social conditions. Being aware of the conditions and the resulting changes in use patterns is useful in planning and can lead to specific management objectives and practices. For example, stronger messages could be issued to inform the recreating public that litter, noise, and resource vandalism are not acceptable. Clean-up patrols could be directed to spend more time in areas where litter is a problem. Managers could close worn-out campsites and portages to allow these areas time to recover. Campsites in good condition could be monitored and corrective actions taken before overuse causes deterioration.

During 1983 Boundary Waters resource administrators will develop a new multi-year management plan. Their management strategy will be based on guidelines outlined in the Recreation Opportunity Spectrum (ROS) system. For management purposes the Boundary Waters has been divided into three of the six zones included under ROS: primitive, semi-primitive nonmotorized, and semi-primitive motorized. Managers there seek to provide different kinds and levels of recreation opportunities for each zone. Information from our study about resource conditions that might influence displacement is one input these administrators will use as they develop carrying capacities for these zones (Sober 1983). For example, campsites might be spaced farther apart in primitive zones than in semi-primitive zones. This action, while controlling the total number of users allowed in primitive zones, would also decrease the chance of hearing or seeing other users from a campsite. Although the study data have limitations, we are encouraged by the response of the resource administrators in the Boundary Waters and what we might learn as they implement new management actions.

Our findings also have implications beyond the Boundary Waters. Other recreation areas across the country have experienced use increases similar to the Boundary Waters, and some people using these areas are probably also being displaced within these areas. In addition off-site displacement is probably also occurring. That is, people are being displaced from one resource area to another.

TABLE 2

Mean Attitude Scores Toward Selected Outcomes

Outcomes Related to Changing Entry Points	Na	Score ^b	Outcomes Related to Changing Campsites	Na	Score ^b	Outcomes Related to Changing Entry Days	Na	Score ^b
See litter along portages	484	-11.05	Find litter in the campsite area	443	-8.83	Come into contact with noisy people	389	-10.88
Come in contact with noisy people	468	-10.82	See peeled birch trees	440	-8.30	Camp within hearing distance of others'		
See litter along the shore	476	-9.46	Camp at heavily used campsites	391	-5.52	campsites	370	-8.75
See worn-out campsites	427	-9.43	Camp within hearing distance of others'			See large groups	291	-8.73
See large groups	347	-9.23	campsites	413	-5.17	Camp at heavily used campsites		
See motorboats	376	-8.41	Camp at sites easily seen from			See motorboats	302	-8.01
See worn-out portages	360	-7.84	others' campsites	371	-5.15	Camp at sites easily seen from others'		
See organizational groups	310	-7.12	See tents of others from your campsite	333	-4.95	campsites	333	-7.51
See other people at entry points	247	-6.34	See watercraft pass by my campsite			See organizational groups	258	-7.40
See people on portages	292	-5.90	Camp close to hiking trails	286	-4.86	See other people at entry points	198	-5.89
See canoes	245	-3.59		310	-1.43	See other people on portages	237	-5.65
						See canoes	193	-3.77

^aThe number of respondents indicating they held both a belief and evaluation about an outcome.

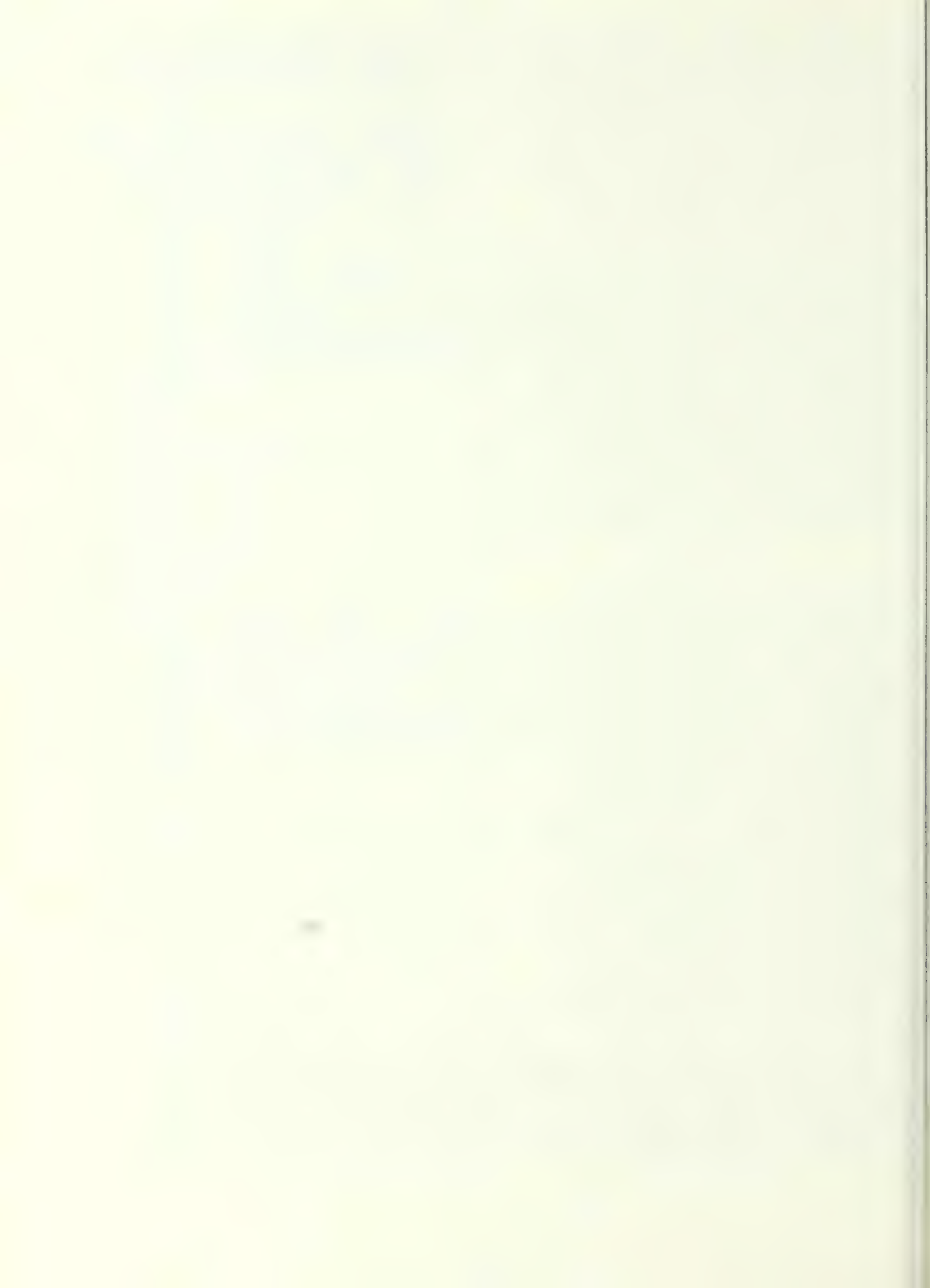
^bScores were obtained by multiplying belief scale values (range = 0 to 6) by evaluation scale values (range = -3 to +3).

For planning and managing purposes, resource administrators need to look at recreation areas within a region and understand how change in one area affects another area. For example, does change in an area signal that new users are coming into the area? If so, should management objectives be written to promote or discourage this kind of change? If objectives are developed to promote succession or new users coming into an area, what happens to the users who were there before? Are they displaced? If they are displaced, where do they go and how do they impact other recreation resources in the region? For those people who are displaced, what kinds of recreation areas and recreation activities do they substitute for the ones they have lost? The answers to these and other similar questions are not known. To answer these kinds of questions, resource administrators at all levels need to know people's preferences for different recreation environments. Equipped with this kind of information administrators can identify recreation areas that are suitable for and capable of sustaining different kinds of users and a variety of uses and, thus, lessen the likelihood of visitor displacement.

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THE HANDICAPPED USER IN OUTDOOR RECREATION RESOURCE

ENVIRONMENTS: IMPLICATIONS FOR RESOURCE PLANNERS¹

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Abstract.--In recent years recreation and resource planners have given increased attention to the provision of outdoor recreation opportunities for individuals with handicapping conditions. Planners are faced with the challenge of designing accessible environments which meet the needs and interests of all users while maintaining the integrity of surrounding natural resources. Current literature provides the planner with valuable information that can guide environmental design and program decisions concerning the handicapped users. This paper presents principles for planning outdoor recreation experiences that are compatible with the expressed needs and interests of many handicapped individuals. It is important that further study be conducted so that planners will have access to a greater knowledge base from which to derive decisions. Recommendations for future research are provided.

INTRODUCTION

Handicapped Americans are increasingly voicing a need for independence, dignity, risk, and adventure. In response to this need, outdoor recreation and resource planners must focus upon the design of environments that are suited to the needs and interests of all users. In recent years, engineers have embraced the study of ergonomics to construct living and work spaces that are highly compatible with the potential users. The application of this science requires a strong technical knowledge of the needs of the consumer, the characteristics or qualities of the environment, and the dynamics of the relationship between the consumer and his or her surroundings. Similarly, the outdoor recreation and resource planner who wishes to design an ergonomic environment which meets the needs and interests of all users while maintaining the integrity of the surrounding natural resources, must have access to technical knowledge concerning the

needs of potential users as well as the recreation resource environment. Only then can design principles evolve which offer the greatest compatibility.

This paper presents the planner with information which can have application to decisions effecting environmental design for handicapped users. Questions to be addressed through future research efforts are also posed. The literature currently available to recreation resource planners focuses primarily upon information concerning the outdoor recreation interests and physical accessibility needs of handicapped people. While further research must be conducted in order that planners have an adequate knowledge base from which to base decisions, current literature does reveal some guidelines for planning. A discussion of selected principles follows.

PRINCIPLES FOR PLANNING

Integrated recreational settings

Handicapped individuals have strongly articulated the need for, and an interest in, recreation facilities and activities, especially in informal, integrated, outdoor recreational settings (Peterson et al. 1977). In the early 1960s the U.S. Forest Service began

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developing highly specialized recreational facilities for handicapped persons, such as the Roaring Fork Braille Trail in Colorado, Mammoth Lakes Campground in California, and Trout Pond in Florida. User feedback indicated that many handicapped individuals were specifically avoiding these segregated areas, preferring to struggle in the inaccessible facilities so they could be with their families and/or the majority of other users. Thus it was learned that some handicapped individuals wished to be included in the mainstream of life, without an inordinate amount of special or separate facilities and programs (Carroll 1973; AAHPER 1977; Fay et al. 1976). Consequently the Forest Service has revised its service philosophy for handicapped individuals. Current practice within the Forest Service is to discontinue development of segregated recreational areas and instead focus upon the elimination of physical barriers which prevent the use and enjoyment of existing forest lands and recreational areas (USDA 1983; Fay et al. 1976).

While this apparent responsiveness of the Forest Service is a positive sign, and will better address the needs of many handicapped individuals, there are still important and relevant questions which go unanswered and may have implications for the current planning approach. Are there sub-groups of potential handicapped users that would prefer and/or need special facilities (e.g. multiply handicapped or severely handicapped individuals)? If so, are there sufficient numbers of potential users within these sub-groups and/or federal legislative mandates which would support at least some highly specialized areas?

Tangential to this planning principle is the concern of handicapped individuals that planners might generalize the findings of a sample of individuals who have one disability to represent or imply the preference of individuals with different disabilities. As there are a myriad of interests and abilities among the nonhandicapped population, so are there among handicapped individuals.

Normalized outdoor environments and activities

Handicapped individuals indicate a preference for activity opportunities and facilities much like those preferred by nonhandicapped peers. Beechel (1975) found that while some special accommodations are necessary to facilitate pursuit of certain outdoor recreation opportunities, handicapped individuals prefer outdoor environments that are as close to normal as possible. In addition, Carroll (1973) found that the types of outdoor recreation preferred by a sample of handicapped in-

dividuals were hiking, water sports, picnicking and camping; experiences that are commonly enjoyed by nonhandicapped peers.

Threshold for adaptation

There is evidence that a threshold level of adaptation appears to exist, beyond which further design changes are likely to be perceived as stigmatizing (West 1981). There are several case study examples in which planners, designers, and programmers have invested dollars, time, and sincere concern in projects that have altered outdoor areas and facilities for the presumed benefit of the handicapped user. Yet, in spite of this investment in improved service capability, it was found that there was no subsequent increase in use of these areas and facilities by handicapped consumers. Contrary to this no increase in use pattern, handicapped consumers, consumer advocates, federal legislative mandates, as well as numerous descriptive research studies validate that design and accessibility improvements in outdoor recreation facilities and programs continues to be a major desire expressed by the potential handicapped user. Thus to what can we attribute this inconsistency between use patterns and interests?

There is some evidence that a threshold level of adaptation appears to exist, beyond which further design changes are likely to be perceived as stigmatizing and as a result, discourage use. A personal experience which occurred during a research study of the accessibility features of New Hampshire State Parks (Powell 1982) tends to further support this claim. Throughout the New Hampshire study, it was noted that most accessible campsites were designated by large, two- by three-foot blue signs displaying the international access symbol. These signs were clearly visible to all passersby. During an interview of a handicapped user who had selected an inaccessible site, the following comments were recorded:

"I come here to get away from the pressures of my job and my handicap. Those signs are like a flashing red light. A man stopped by my campsite today and didn't realize one of my legs was missing until thirty minutes later when he asked me if I would help him put his boat in the water. I reached for my crutches under the picnic table and stood up. He gasped. I don't think he would have ever stopped by if I had camped at a site that had one of those signs. As it happened, I was able to help him relax around me and we're off on a fishing trip in the morning." Viable alternatives to this more stigmatizing prac-

ice of obtrusively posting access signs might include dissemination of information on accessible campsites at time of check-in and/or identification of such sites on camp maps and other literature.

This handicapped user's story suggests additional unanswered questions, e.g. Is this handicapped individual's feelings characteristic of many other individuals? Are there particular types of adaptations that handicapped individuals find especially stigmatizing? Are there alternative means to facilitate use that are less stigmatizing?

Continuum of opportunities

Not all persons with handicapping conditions desire the same level of outdoor adventure experiences. As with the general population, adventure is a personally defined experience. "Just as some able-bodied persons prefer more challenging primitive wilderness areas while others want campgrounds with all the comforts of home, some individuals with handicapping conditions want longer and more difficult hiking trails than other handicapped persons." (AAHPER 1977, p.67). Implications for planning that may be derived from this principle are numerous. For example, it becomes important to offer a continuum of outdoor recreation opportunities and settings for handicapped individuals due to the consequent diversity of needs and preferences which must be met -- a planning principle which is already applied to the nonhandicapped population.

Trail design and information.--Consistent with this thinking is the practice of placing signs at the entrance of outdoor trails that inform potential users of the trail length, the level of difficulty (using a national rating scale much like those used for ski slopes) and a map indicating the location of rest stops and accessible toilet facilities. This information will allow each potential user (whether handicapped, nonhandicapped, elderly, or small child) to make personal choices about taking the trail based upon individual ability. Other alternatives that should be considered for hiking trail accessibility are the all-terrain vehicle, snowmobiles, gondolas, or horseback riding, all of which can be realistic means of mobility over natural terrain for many handicapped individuals. Provision of trails with varied gradations and 3/8ths minus crushed rock can also offer opportunity for all users without being costly or aesthetically damaging (Helbig 1978). The cries and concerns of some resource planners that all natural areas will soon be covered with black-

top in order to accommodate the handicapped can be alleviated.

Trails for blind individuals.--The trails enjoyed most by blind persons are those that have been left in as natural a state as possible (as long as they are safe). Such a state affords a more challenging experience (Beechel 1975; Fay et al. 1976; AFB 1972). Research by the U.S. Forest Service and the National Park Service indicates, "while braille trails are popular with sighted visitors, they are usually useless to the blind individual" (Fay et al. 1976). This conclusion is based upon the following facts: 1) less than ten percent of blind individuals can read braille; in addition, there are several 'languages' of braille; and 2) braille signs are highly subject to vandalism. Alternative solutions to accessibility have included the use of audio interpretive devices such as tape recorders in lieu of signs, use of 'differential' trail surfaces which by feel and/or sound distinguishes the trail from its surroundings making trails safe from obstacles, and making trails interesting to all the senses (Beechel 1975; AAHPER 1977; Fay et al. 1976). An example of such a trail is in the New Jersey Pine Barrens which stresses pond ecology, forest management, and plant and animal relationships.

Benefits to all users

Physically handicapped individuals are not the only persons who benefit from barrier-free access designs. Reports have shown that there are fewer tripping and falling hazards and therefore fewer public liability claims and worker related accidents in barrier-free settings. Ramps and wider door construction meet with the highest fire prevention standards, so buildings with barrier-free design generally have lower insurance rates (Harris et al. 1977). A survey at the University of Kansas concerning new curb cuts installed on campus found that people interpreted the reasons for the improvement in terms of their own life situation, not as improvements for the handicapped. Ninety percent of the respondents felt the curb cuts were made to help bicycle riders, and those respondents who were service employees felt the curb cuts were made to facilitate deliveries (Harris et al. 1977).

Cost of accessibility

Finally, it should be noted that while plans to make new and existing facilities and areas accessible may incur additional costs, surveys conducted by the General Accounting Department of HEW indicate that "in new con-

struction, the additional cost for accessibility is less than one-half of one percent and renovating existing facilities, no more than three percent" (AAHPER 1977). In addition there are 'low cost' or 'no cost' approaches to establishing accessible environments that are frequently overlooked. Examples include: placing cup dispensers beside water fountains for wheelchair users; tilting bathroom mirrors when they cannot be lowered; providing an accessible unisex bathroom so that companions can assist their handicapped partner; asking the telephone company to lower a telephone; using taped messages when possible; and changing door weights so they may be opened with less effort.

DIRECTIONS FOR FUTURE RESEARCH

A review of existing outdoor recreation research literature indicates the following:

1) There is little evidence of empirical studies that have specifically examined the handicapped user.

2) Few existing studies pertaining to nonhandicapped user characteristics and behavior have been validated with reference to the handicapped user. Research theory that has been applied to nonhandicapped user behavior patterns and preferences may indicate approaches for expanding the relevant knowledge base of planners. For example, the Opportunity Theory has been tested using a population of different socioeconomic groups, but the literature appears to be void of such hypothesis testing with handicapped individuals. The fact that handicapped people in the U.S. have on the average significantly lower earnings than the nonhandicapped suggests the potential relevance of study in this area.

Recreation researchers have also investigated the causes of conflict among users of outdoor recreation with regard to the concept of goal interference. "Lifestyle tolerance", the tendency of accept or reject lifestyles different from one's own, was derived by Jacop and Schreyer (1980) as one of the major classes of factors which produce conflict in outdoor recreation. The nature and extent of user interaction among handicapped and nonhandicapped individuals may have serious implications regarding the success with which handicapped individuals are integrated and accepted into traditionally nonhandicapped environments. This author could not identify any existing research which supports or refutes user conflict/goal interference using the independent variable of noticeable

handicapping conditions.

3) Much of the research to date with respect to outdoor recreation participation of handicapped individuals has focused upon physical design barriers. It has been hypothesized that physical removal of architectural barriers will result in a significant increase in participation of handicapped individuals. While there is little argument that barrier-free design presents increased opportunity there is evidence that removal of barriers in and of itself will not guarantee use. Researchers have only just begun 'to scratch the surface' in terms of studies which focus upon intervening variables that may have an impact upon the use of physically accessible facilities.

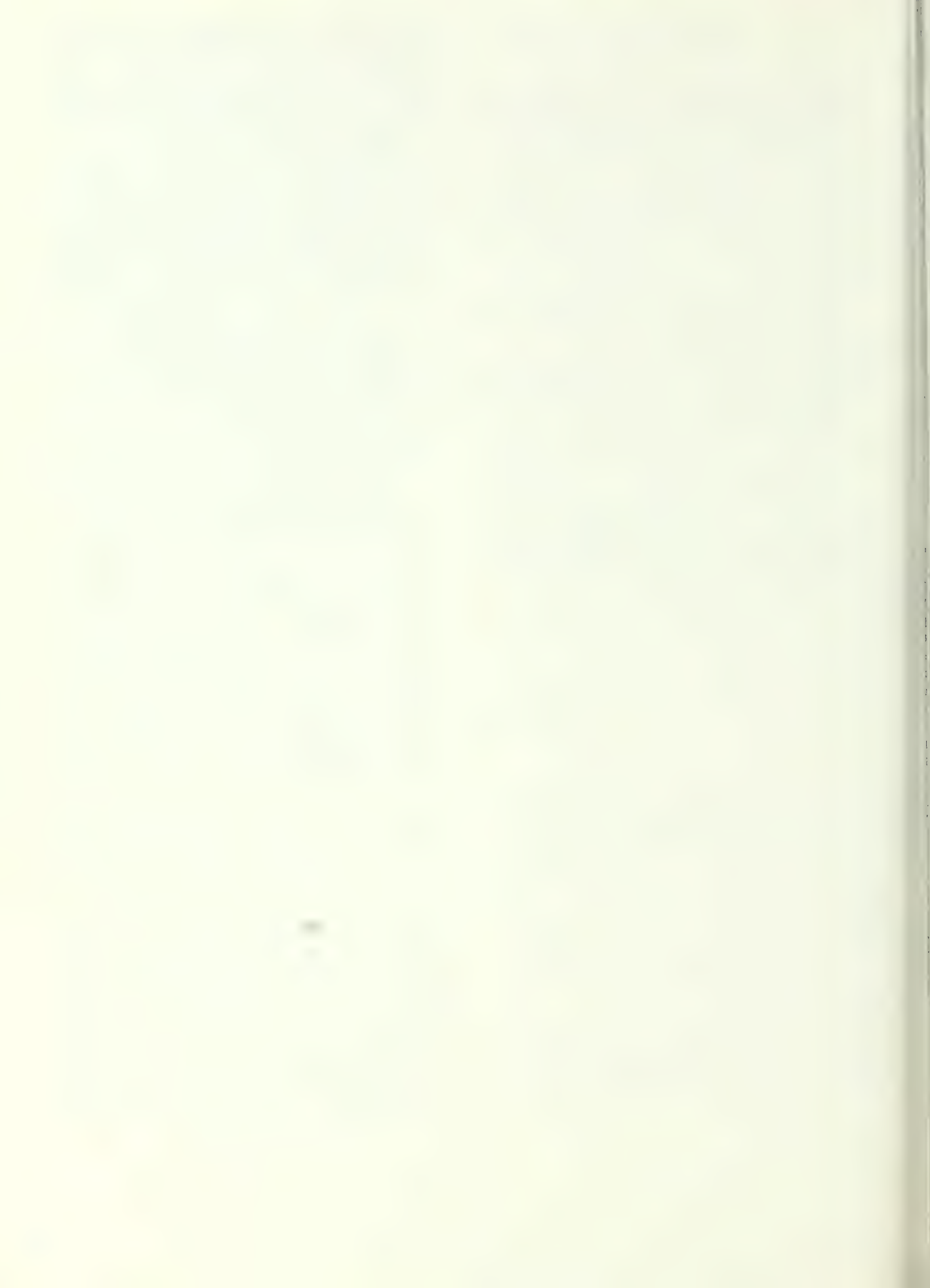
4) Most of the research that has examined the benefits of outdoor recreation for handicapped individuals has taken place in segregated camp settings. More research is needed in areas that are used by the general public such as national and state parks, national forests, natural centers, and backcountry and wilderness areas.

Further, it appears that existing research which has potential application to the handicapped user in the resource environment appears to be dichotomous in nature. There is a body of descriptive research which focuses upon the expressed outdoor recreation needs and interests of handicapped persons. This research has been conducted primarily by professionals in Therapeutic Recreation and the allied health fields. Another body of empirical and descriptive research exists which explores the behavior of the nonhandicapped user as well as the environmental impact of these users. This research has resulted in recreation resource planning and management.

A greater convergence of these research efforts is needed. Our research knowledge base concerning the handicapped recreation resource consumer can be greatly enhanced if our investigations are expanded to include study of use patterns, participant behavior and environmental impacts of these users. Further study of variables that potentially inhibit or facilitate use of resource environments by handicapped users is imperative. The author encourages researchers who investigate recreation resource user behavior to include the handicapped user as a variable when feasible. Collaboration of those researchers who are knowledgeable about issues concerning handicapped persons with researchers who have expertise in recreation resource planning can potentially result in new planning principles which will lead us toward a more ergonomic environment for all natural resource users.

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DEER DENSITIES AND FOREST REGENERATION¹

by Nancy G. Tilghman²

Abstract.--Preliminary results of a study of the effects of five deer densities and three cutting treatments on development of tree seedling reproduction on the Allegheny Plateau of northwestern Pennsylvania show that higher deer densities reduce the height growth made by seedlings in clearcut and thinned stands. Moreover, there are fewer tree seedling species, less Rubus, and more fern at higher deer densities.

INTRODUCTION

The Allegheny hardwood forest type covers nearly 12 million acres in Pennsylvania, New York, Maryland, and West Virginia (Fig. 1). The major tree species of these forests are black cherry (Prunus serotina Ehrh.), red maple (Acer rubrum L.), sugar maple (Acer saccharum Marsh), and white ash (Fraxinus americana L.). Most of the world's supply of cherry lumber and veneer for furniture and paneling comes from these forests. The maples are used for furniture, flooring, and specialty products, and the white ash are used for baseball bats and tool handles (Marquis 1975). The overall value of timber in the cherry-maple forests of northwestern Pennsylvania averages about 2500 per acre. Timber receipts on the Allegheny National Forest alone run between 4 million and \$6 million per year.³

The Allegheny hardwood forests of northwestern Pennsylvania are valuable for other reasons as well. Over 100 million people live within a day's drive of these forests and many of them take advantage of the recreational opportunities for camping, hiking, and boating there (U.S. Forest

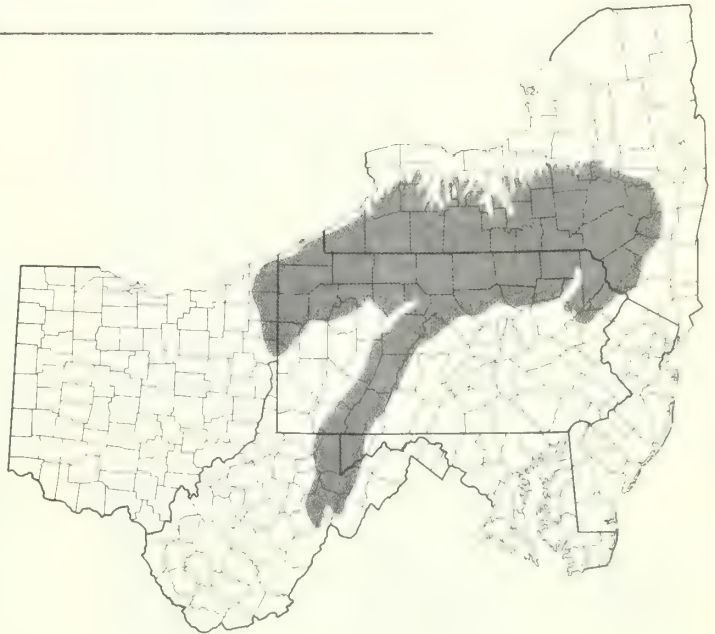


Figure 1.--Distribution of the Allegheny hardwood forest type.

Service 1975). The beautiful scenery, especially the spectacular fall foliage, attracts many city-dwellers to the cherry-maple forests. These forests are the home of numerous species of wildlife. Many visitors to these forests enjoy the chance to observe animals in the wild; others come to hunt deer, turkey, grouse, and bear. Over 1.25 million people buy hunting licenses in Pennsylvania, more than in any other state in the nation.

But the future of these forests is in jeopardy because there are not enough young tree seedlings to replace the overstory trees after harvest. Although there are several interrelated reasons for this, browsing of seedlings by white-tailed deer (Odocoileus virginianus) is a major one.

¹Paper presented at the Symposium on Research in Forest Productivity, Use, and Pest Control: Contributions by Women Scientists, Burlington, Vermont, September 16-17, 1983.

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³Personal communication from J. Hockinson, Timber Staff Officer, Allegheny National Forest, USDA Forest Service, Warren, Pennsylvania, 1983.

BACKGROUND

A look at the future of these forests must begin with a brief look at the past. Before it was settled by white men, white pine-hemlock-hardwood forests covered much of this area. Clearcut logging of these forests between 1890 and 1930 resulted in today's cherry-maple forests (Marquis 1975). Thus, these second-growth forests are essentially even-aged and most are between 50 and 110 years old (Fig. 2). Nearly three-quarters of these stands will be ready to harvest in the next few decades, but because regeneration is inadequate their owners hesitate to harvest them.

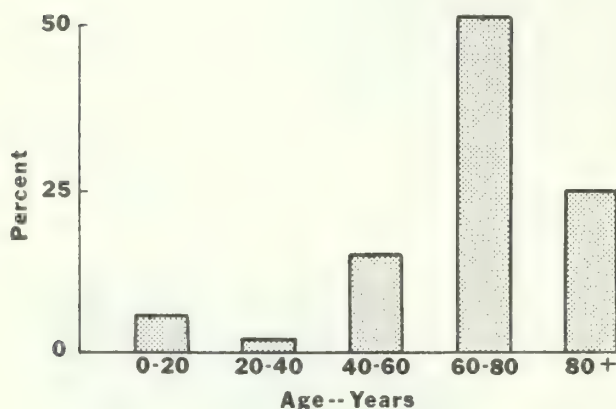


Figure 2.--Age-class distribution of Allegheny hardwood forests in northwestern Pennsylvania.

Although it is difficult to separate the history of white-tailed deer populations in northwestern Pennsylvania from that of the rest of the state, a statewide review of deer population trends suggests what happened in the Allegheny hardwood forests. In the late 1800s, white-tailed deer populations were subject to intense hunting pressure. Deer were hunted for market and sold to the many logging camps around the state. There were no laws restricting the number or sex of deer that could be taken or the season when they could be hunted. Dogs and baits were commonly used in the pursuit of deer. By the turn of the century, deer had nearly been eliminated from Pennsylvania (Forbes et al. 1971). Then several steps were taken to protect the remaining deer, including the institution of a "bucks only" hunting season. Deer were brought in from other states and introduced to areas from which they had been extirpated. At the same time, extensive clearcutting provided an abundant food source for the deer. The combination of protection from overhunting, abundant food, and the lack

of natural predators allowed the deer population to increase dramatically (Fig. 3) (Forbes et al. 1971).

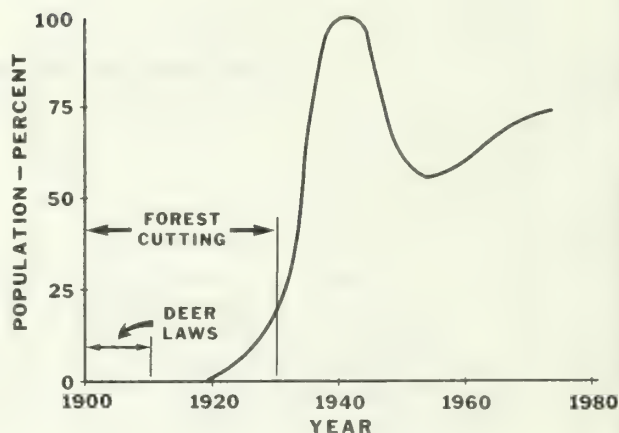


Figure 3.--Deer population trends in Pennsylvania. After Marquis (1975), adapted from Leopold (1943), Bennett (1957), and records of Pennsylvania deer harvests.

By the early 1920s, deer damage to forest reproduction was evident (Frontz 1930). As the new forests grew out of the reach of the deer, deer food became scarce. The loss of previously abundant food resources and lack of overstory cover caused widespread winter starvation by the late 1920s. In 1928, the taking of does was legalized throughout Pennsylvania in an attempt to curb population growth. Nevertheless, deer numbers in Pennsylvania probably reached a peak of about a million deer by the late 1930s (Forbes et al. 1971). But the doe seasons, increases in the total harvest, and large winter losses reduced the deer herd to about half its peak by 1950 (Bennett 1957). Since that time, statewide deer populations have gradually increased to about 750,000 deer (Fig. 3).⁴

The problem of high deer populations browsing on tree seedlings to the point of greatly altering or even eliminating the new generation is not unique to northwestern Pennsylvania. Foresters and biologists have noted this conflict between forest and wildlife resources in other areas of the

⁴Comparison of population estimates of the statewide deer herd is confounded by changes that have occurred in the method of estimating deer populations. While the actual numbers may not have been accurate in past years, the general population trends indicated by these estimates are useful.

country (e.g. Washington, Oregon, Wisconsin, Michigan, New York) and at various times since the beginning of forest management.

ALTERNATIVES

Over the years, several techniques have been developed to alleviate the overbrowsing of tree seedlings. On the Allegheny plateau, numerous repellents have been tested, from those that taste terrible to those that smell rotten. None of these have proven effective in reducing browsing at high deer densities. At low deer densities, some repellents have been effective, but they require frequent and expensive reapplication.⁵ Aerial application of nitrogen and phosphorous fertilizers to induce rapid height growth of existing seedlings beyond the reach of the deer has been tried, but this, too, is expensive (Auchmoody 1982). Fencing regeneration cuts has also proven effective, but again a sizable expense must be borne by the landowner. Electric fences can cost from \$17 to \$160 per acre (Brenneman 1982), while 8-foot woven wire fences cost from \$100 to \$350 per acre.⁶

Although these techniques may provide short-term protection of small areas from deer browsing, they are only bandaid solutions. Those who manage the deer herd and its habitat have been working together to come up with a long-term compromise that will ameliorate the economic and ecologic impact of high deer populations on forest resources. The first step in the process is to bring the deer herd down to level at which the forests can be regenerated.

MANAGING THE DEER HERD

The Pennsylvania Game Commission (PGC) manages the state deer herd on a county-by-county basis. They have developed deer population estimates for each county. For example, their overwintering deer density estimates for the four counties in which the Allegheny National Forest is located range from 15 to 30 deer per square mile.⁷ Using forest age-class information, the PGC has

also developed deer population goals for each county based on the overwinter carrying capacity of forests of various ages. In three of the counties mentioned above, the PGC has set goals that call for a decrease in the county-wide deer population, while in the fourth they want to maintain the population at nearly the same level.⁷ Although these goals are based on the best information presently available, they come primarily from studies of deer condition and survival. They are not goals for deer population levels that will allow adequate tree reproduction. We need better information on which to base our management strategies. Just what is the optimum deer density that will allow hikers and hunters to enjoy deer in the forest, but still allow enough tree seedlings to survive to perpetuate the forest?

ENCLOSURE STUDY

The U. S. Forest Service's Northeastern Forest Experiment Station at Warren, Pennsylvania, has initiated a 10-year study of the effects of several deer densities on tree regeneration in Allegheny hardwood forests. A second objective of this study is to examine the preferences of deer for browse among the numerous species of woody and nonwoody understory plants.

Methods

Four 160-acre enclosures have been established in Allegheny hardwood stands of northwestern Pennsylvania. Two of these sites are located on the Allegheny National Forest, one is located on State Game Land 30, and one on Elk State Forest and National Fuel Gas forest land (Fig. 4). Each of these enclosures has been constructed of 8-foot woven wire fencing and has been subdivided into four subenclosures. Different deer densities have been established in each of the subenclosures with one deer in 64 acres and one, two, and four deer in each of the 32-acre areas, simulating 10, 20, 40, and 80 deer per square mile (Fig. 5). Small exclosures (1/250 acre) were randomly placed in each subenclosure to represent zero deer per square mile. Each subenclosure was also subjected to three different cutting treatments-- 10 percent was clearcut, 30 percent was thinned, and the rest was left uncut.

A system of permanent milacre sampling plots was established in each subenclosure, with 25 plots in the clearcut, 15 plots in the thinning, and 20 in the uncut portion. The height and number of each species of tree seedlings on these plots were tallied before deer were installed; they will be remeasured every other year over the 10-year period.

⁵Office report (Study 98) by R. Ernst, USDA Forest Service, Northeastern Forest Experiment Station, Warren, Pennsylvania, 1980.

⁶Personal communication from J. Hockinson, Timber Staff Officer, Allegheny National Forest, USDA Forest Service, Warren, Pennsylvania, 1981.

⁷Personal communication from W. Shope, Wildlife Biologist, Pennsylvania Game Commission, Millerstown, Pennsylvania, 1983.

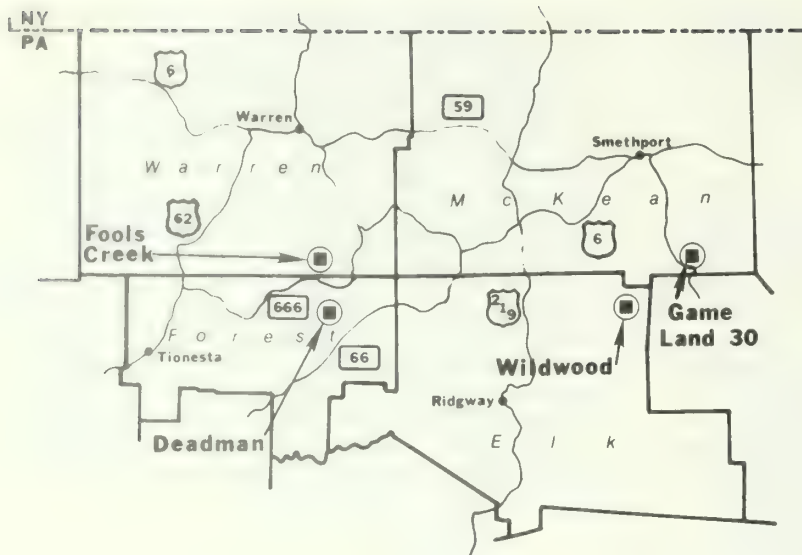


Figure 4.--Location of study areas.

The percentage cover of various herbaceous plant species has also been recorded and will be monitored throughout the study.

Preliminary results

This past summer we took the first remeasurements of vegetation on two of the four study areas and already we can see differences in the vegetation. Some differences are the result of cutting treatments, but others can be attributed to the density of deer. In the clearcuts, differences in the height of tree seedlings are readily visible. For example, in the 10-deer/square-mile clearcut, the average height of the tallest tree seedlings is nearly 7 feet (Fig. 6a). In the 80-deer/square-mile clearcut, however, the dominant seedlings are not yet 4 feet tall (Fig. 6b). Most of the tallest seedlings in the high-deer-density enclosures were located in slash piles where they escaped browsing. The average height of seedlings outside the slash piles in the 80-deer/square-mile clearcut was less than 2 feet.

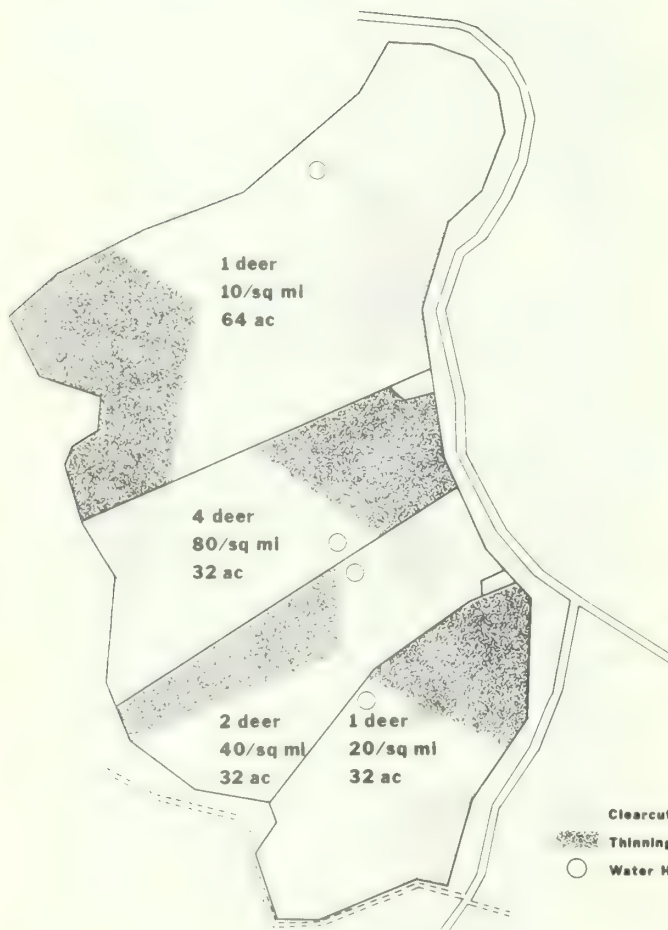


Figure 5.--An example of the layout of one of four deer enclosures.

Unprotected seedlings in our highest deer density enclosures were significantly shorter than seedlings in any of the other densities, protected or unprotected (Table 1). The protection offered by slash in the two highest deer density treatments allowed seedlings to grow as tall as those found in unprotected areas of the lower deer density enclosures. At low deer densities, seedlings located in slash piles were as tall as those found in our control areas inside the enclosures. Thus, slash left on the ground after a clearcut can provide protection for the new seedlings and result in a shorter rotation for the new stand.



Figure 6a. Height growth of tree seedlings in the 10-deer/square-mile clearcut.

Table 1.--Comparison of effects of slash on the height of tree seedlings in different deer densities.

Height of dominant stems		
< 2'	3' - 5'	> 7'
80 deer ^a - no slash	80 deer - slash	0 deer - no slash
	40 deer - no slash	0 deer - slash
	40 deer - slash	10 deer - slash
	20 deer - no slash	20 deer - slash
	10 deer - no slash	

^adeer = deer per square mile.

We are also beginning to see evidence of changes in the species composition of the regeneration from different deer densities. In the 10-deer/square-mile treatment, a wide variety of tree seedling species can be found--black cherry, red maple, sugar maple, white ash, yellow-poplar (*Liriodendron tulipifera* L.), American beech (*Fagus grandifolia* Ehrh.), sweet birch (*Betula lenta* L.), yellow birch (*Betula alleghaniensis* Britton), aspen (*Populus* spp.), cucumbertree (*Magnolia acuminata* L.), pin cherry (*Prunus pennsylvanica* L.), striped maple (*Acer spicatum* Lam.), serviceberry (*Amelanchier* spp.), devils-walkingstick (*Aralia spinosa* L.), and staghorn sumac (*Rhus typhina* L.). Black cherry and pin cherry seem to dominate. In the clearcut, many of these young black cherries are stump sprouts. The diversities of tree seedling species in the 80-deer/square-mile treatments at the two study areas were different. At one site where the regeneration potential was high, the number of tree seedling species was nearly the same as that found in the low-deer-density subenclosures (Table 2). The abundance of seedlings and more rapid height growth on this good site allowed a



Figure 6b. Height growth of tree seedlings in the 80-deer/square-mile treatment.

wider variety of tree seedlings to grow out of the reach of deer. At the other study area, however, there were significantly fewer tree seedling species in all cutting treatments of the high-deer-density subenclosures (Table 2). Because they are preferred browse, species such as pin cherry are significantly less common in the 80-deer/square-mile treatment. Only the less palatable species are left, and there is a tendency for black cherry to dominate. Although black cherry is our most valuable timber species, this shift toward a monoculture of black cherry is considered undesirable from both timber and wildlife management viewpoints. A monotypic forest runs the risk of complete destruction by insects or disease and decreases the diversity of wildlife habitats available.

Table 2.--Number of seedling tree species by deer density and cutting treatment for two study areas, one of high reproductive potential and one of lower reproductive potential.

Cutting treatment	Reproductive potential	Number of deer per square mile				
		0	10	20	40	80
Uncut	High	9	8	8	7	8
	Low	11	12	8	10	7
Thinning	High	10	8	10	10	8
	Low	13	12	13	9	9
Clearcut	High	10	10	11	11	10
	Low	12	12	10	11	10

Changes are also apparent in the relative abundance of certain herbaceous species. Ferns cover nearly four times as much area in the high deer density clearcuts as they do in the lower deer densities (Table 3). These ferns, primarily hayscented fern (Dennstaedtia punctilobula (Michx.) Moore) and New York fern (Brachelytrum erectum Schreb.), produce chemicals that interfere with the germination, growth, and survival of young black cherry seedlings. Blackberries (Rubus spp.) are also affected by high deer densities. In the high deer density thinnings, deer have reduced the amount of blackberry cover by 50 to 75 percent as compared with the low deer density thinnings (Table 3). Blackberries, a favorite food of deer, are not abundant where deer browsing is heavy. Just as ferns have been shown to interfere with tree seedlings, so blackberries have been shown to interfere with ferns and grasses. Thus deer browsing not only has a direct effect on the growth and survival of tree seedlings, but can indirectly affect them as well by eliminating the blackberries that would ordinarily limit the spread of ferns and grasses.

Table 3.--Percent ground cover by ferns and Rubus at different deer densities.

Ground cover	Cutting treatment	Number deer per square mile				
		0	10	20	40	80
Fern	Clearcut	6	3	10	24	15
Rubus	Thinning	70	64	70	50	10

RECOMMENDATIONS ?

With only two of the four areas remeasured, our results are in no way conclusive. It is still too early to come up with any recommendations for desired deer densities to benefit both wildlife and forestry resources. But even after 2 years, we are witnessing changes in the vegetation, changes that affect not only the future forests of the region, but habitat for other wildlife species as well. When deer populations are too high, the natural understory of the forest may be eliminated. In some instances, deer may compete directly for food items with other wildlife, such as snowshoe hare (Lepus americana) and wild turkey (Meleagris gallopavo). Cover, roosting, or nesting sites may be eliminated for other wildlife species such as ruffed grouse (Bonasa umbellus) and low-nesting songbirds (Passeriformes). These changes in the forest happen gradually as the deer herd builds up, so it is often difficult to

attribute changes in the abundance of other wildlife species to the deer. For those species whose territories or home ranges are small enough, we will be looking for population differences among the various deer-density treatments. To date, a study of songbird diversity and abundances has been initiated in these enclosures. High deer populations can also have an effect on the deer themselves. Several studies have shown that deer raised on poor nutrition will generally be in poorer physical condition. Bucks tend to have smaller racks, and does tend to produce twins less often. Thus, reducing deer densities to levels compatible with existing range conditions can improve the outlook for both forests and wildlife.

As efforts are being made to bring the deer herd more in line with the habitat available, other efforts are underway to provide better deer habitat. The Allegheny National Forest has developed a cooperative agreement with the Pennsylvania Game Commission which not only calls for a reduction in the local deer herd, but requires that the National Forest make regeneration cuts totalling at least 2000 acres per year and at least 7000 acres of thinnings or initial shelterwood cuts. These measures are designed to provide additional food for deer and to spread the deer out over a wider area. These efforts to manage both the deer and its habitat will benefit the entire forest ecosystem including the deer, other wildlife species, and the new forest regeneration.

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PATTERNS OF WOLF PREDATION
AND EFFECTS ON MOOSE FEEDING HABITATS¹

Joan Edwards²

Abstract.--Observations of moose (Alces alces andersoni) were made at the northeastern end of Isle Royale Wilderness National Park, Michigan, to determine the food preferences, distributions and diets of moose. Moose show strong food preferences which correlate with nutrient content. Adult bulls, solitary cows and yearlings shift distribution so that they track these high preference, high nutrient food items. In May and June, they feed on the ridges of the main island where high nutrient food items are first available; only in July and August do they move to the small outer islands where high quality foods are available later. Cows with calves deviate significantly from this pattern by going to the small islands in May prior to the leafing of high nutrient foods and remaining there throughout the growing season.

These distributions of moose suggest that wolf predation may significantly alter the feeding patterns of cows with calves, the age class most vulnerable to wolf predation. Cows may protect their calves from wolves by remaining on the wolf-free outer islands and avoiding the main islands where wolves are present. These data suggest that wolves not only affect moose population dynamics directly through kills but also indirectly by altering the diet of reproductive cows, those individuals that most directly contribute to population growth.

INTRODUCTION

The wolf (Canis lupus) and moose (Alces alces andersoni) populations on Isle Royale, Michigan have been carefully monitored since 1959 and historical records as well as intermittent studies are available for 1904-1958 (Mech 1966, Peterson 1977). The population trends suggest a classic example of a predator stabilizing the population dynamics of their major prey species. Prior to the wolves' arrival on Isle Royale, the moose showed oscillating population size; after

the wolves' arrival, moose population size was relatively stable.

Although the wolf and moose population dynamics on Isle Royale are among the most well documented for a large mammal predator-prey system (Frenzel 1974), the moose-plant interaction on Isle Royale is less well understood. The purpose of this paper is to report behavioral evidence that the moose-plant interaction is, in part, mediated by wolves. This study suggests that wolves not only affect the moose population directly through kills but also indirectly by altering the diet of cows with calves, those individuals that are most important in contributing to population growth. First I use behavioral evidence to establish the location and types of high quality foods. Then I examine whether the presence of wolves deters moose from feeding on the high quality plants and in the best feeding areas.

¹ Paper presented at a symposium on Research in Forest Productivity, Use and Pest Control: Contributions by Women Scientists, Burlington, Vermont, 16-17 September 1983.

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General Information

This study was carried out on Isle Royale National Park in Lake Superior, Keweenaw Co., Michigan (48° 10' N, 88° 30' W) from May through September 1974-1976. The land area of the park covers 210 square miles and consists of a main island (72km long and 14km wide at its widest point) and approximately 200 smaller islands. The closest shore to Isle Royale is the Canadian north shore which is 21km to the northwest. The study site is located at the northeastern tip of Isle Royale and includes the northeastern tip of the main island and 44 peripheral islands. The topography is characterized by parallel ridges and valleys (elevation on the main island sites in the study area vary from 183m at Lake Superior level to 329km at Mt. Franklin; the small islands are all fairly low-lying with none exceeding 24m above lake level). The primary forest type at the northeastern end of Isle Royale is boreal White spruce (*Picea glauca*)-- balsam fir (*Abies balsamea*)-- paper birch (*Betula papyrifera*) forest (Cooper 1913, Brown 1937, Linn 1957).

Isle Royale is a particularly good natural laboratory for several reasons. First it is an isolated and bounded system. Since there is little interaction between animal populations on Isle Royale and those in Canada (Mech 1966, Peterson 1977), emigration

and immigration do not have to be monitored. Second, it is a wilderness national park and therefore no hunting is allowed. This is particularly important for behavioral studies of moose since it is easier to get good observations of moose in non-hunted populations (Geist 1971, Goddard 1970). Finally, Isle Royale has a relatively simple food web. Islands traditionally have fewer species than mainland sites (MacArthur and Wilson 1967). For example, bears, white-tailed deer and coyotes which are all found on the Canadian north shore are absent from Isle Royale. Therefore there is one dominant food chain, wolves which eat moose which, in turn, eat plants.

Population dynamics of moose and wolves

The population trends of both moose and wolves, based on data from Mech (1966) and Peterson (1977), are summarized below and in Figure 1.

³ There is some variation in this food chain. For example, wolves also include beaver, hare, birds and plants in their diet. See Peterson (1977) for a detailed analysis of wolf diets on Isle Royale.

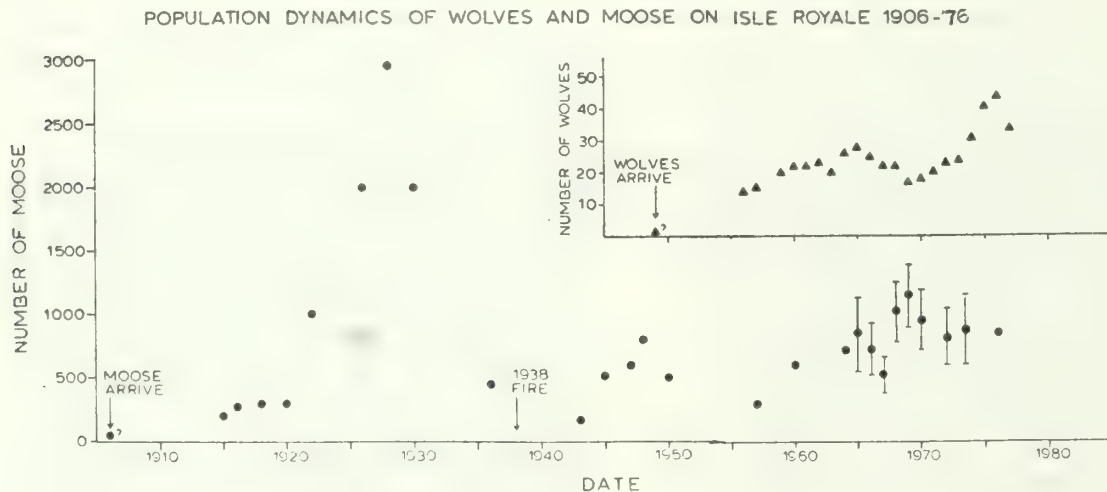


Figure 1.--Population trends of moose (•) and wolves (▲) on Isle Royale from 1906-1976. Data are from Mech (1966) and Peterson (1977). The early moose estimates, those without bars, are based on ground counts or strip aerial surveys. The error for these estimates is potentially high (e.g., the estimate of moose population size in 1930 was 1,000 -3,000; for such cases, the mean of the two extremes is represented on the figure). The later estimates, those with bars, are based on stratified aerial surveying. The bars represent 95% confidence intervals.

Moose.-- Moose probably arrived on Isle Royale by swimming from the Canadian north shore. Although the exact date of their arrival is uncertain, early observations by Adams and Hickie (Mech 1966) indicate moose arrived on Isle Royale about 1905. The moose population initially showed an exponential or "J-shaped" growth pattern increasing from about 200 moose in 1915 to an estimated 2,000 moose by 1925 (Mech 1966). The moose then presumably began to deplete their food supply and the population crashed to less than 200 by 1943. Regrowth of the vegetation due to both low moose population levels and to a fire that burned approximately 1/3rd of the island in 1938, allowed the moose population to grow until the arrival of wolves. Then there was a drop in the moose population in the 1950's, a gradual rise during the 1960's, and a slight decline during the 1970's (Mech 1966, Peterson 1977).

Wolves.-- Wolves probably arrived on Isle Royale during the late 1940's by walking across the ice from Canada, although there are some reports that wolves were present earlier (Mech 1966). In general, with the exception of a slight decline during the 1960's, the wolf population has been increasing. The Isle Royale population is famous for being the densest known wolf population (Jordan et al. 1967).

Effects of wolves on moose population dynamics.-- Although it is difficult to determine the effect of wolves on the moose population based on comparative data alone, the population trends suggest that the wolf population has stabilized the moose population by preventing wide oscillations in moose population size. The assumption is that the wolves are keeping the moose population at a level where the direct effects of food supply are not the primary limiting factor. However, evidence of nutritional stress and malnutrition are still evident in the moose population. Peterson (1977) reports depleted fat in the bone marrow, decreased winning rates, and decreased calving rates, all of which indicate poor nutrition. In addition not all moose deaths can be accounted for by predation. Wolves at most only account for about 2/3rds of the mortality in the moose population (Peterson 1977); the remainder may be related to malnutrition.

Effects of wolves on moose-plant interactions.-- The evidence of malnutrition suggests that the moose-plant interaction contributes to mortality in the moose population. In this paper, I report behavioral evidence that wolves mediate the moose-plant interaction by limiting cows with calves to wolf-free areas that are poor feeding sites.

MATERIALS AND METHODS

To determine the food preferences,

distribution and diets of moose, I used two methods, direct observations and vegetation sampling.

Observations

To find moose, I followed regular routes, either on foot or in non-motorized boats. When moose were sighted, they were observed for as long as possible. For each observation the date, location and class of moose (adult bulls, cows without calves, cows with calves, and yearlings) were recorded. Then I recorded their diet in terms of the number of bites of each plant species (June-August). During May, I was only able to record the number of bites of three categories of food (winter foods, herbs and shrubs) since the leaves of deciduous herbs and woody plants were too small to be easily identified. Plants were identified while the moose were feeding or immediately after the animal had left the feeding site. Binoculars (8x24) were used as visual aids. Shannon-Weiner indices of diversity (H') and evenness (J') (see Pielou, 1974, for discussions of H' and J') were calculated for each detailed feeding observation (from the beginning of the observation to the beginning of rumination).

Vegetation sampling

Temporal availability of food items.-- To determine the temporal availability of food items, plant leafing patterns were determined from a 790m long permanent transect perpendicular to the main ridge of the main island extending from the south shore at the base of Tobins Harbor (elevation 183m) to the top of the Greenstone ridge (elevation 262m). Permanent sampling sites were marked at 20m intervals. At each site, the number and type of plant species within a meter distance of the sampling point were noted. At time intervals of 4 (1974) or 10 (1975 and 1976) days, each site was checked, and for each plant species present, initial bud break was noted and the length of the longest leaf was measured.

Food preferences.-- To determine food preferences among herb species, I sampled Minong Island (3.6ha) for eaten and uneaten herbs. There were 19 parallel transects at 1-50m intervals perpendicular to the ridge of the island. Along each transect 1-m² quadrats were censused at 1-10m intervals (Fig.2). A total of 262 quadrats were censused by recording all herbaceous shoots and scoring them as eaten or uneaten. Preference rankings were based on both the proportion of shoots eaten (number of eaten shoots sampled of species A/total shoots sampled of species A) and on pairwise comparisons. For each pairwise comparison only quadrats which 1) had a minimum of one eaten shoot (indicating that a moose had been to the site) and 2) were comprised of at least 80% of the two species being compared were used in the analysis.

The food preferences among species of de-

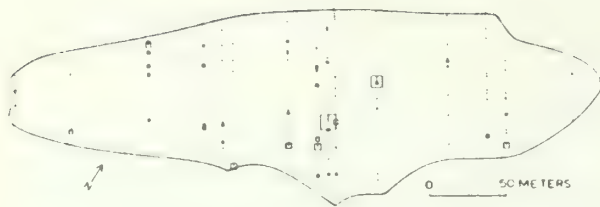


Figure 2.--Sampling sites on Minong Island. Each line of dots represents a transect; each dot a sampling site where a 1-m² quadrat was censused for eaten and uneaten herbs.

ciduous trees and shrubs are based on studies by Belovsky and Jordan (1978) and Edwards (1978).

RESULTS

Food preferences of moose

Moose show clear preferences in food choice. Their seasonal shifts in diet delineate three broad categories (Fig.3). During the

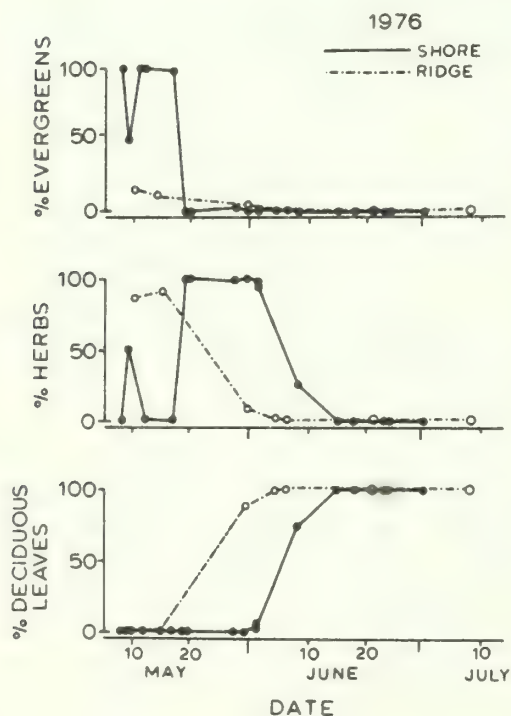


Figure 3.--Comparisons of diets of moose at shoreline and ridgetop sites, 1976. Each symbol represents one feeding observation.

winter when no other foods are available, they feed exclusively on winter foods (woody twigs, evergreen needles and lichens). However, as soon as new leafy vegetation is available, moose switch to eating herbs, the first plants to leaf in the spring. Finally when leaves from deciduous trees and shrubs are available, moose switch to eating them and continue to eat them almost exclusively for the remainder of the growing season. Thus three categories of foods can be listed in order of preference from the most preferred to least preferred: leaves from deciduous trees and shrubs, leaves from herbs and winter foods.

The herbs can be further subdivided into high preference and low preference herbs. First, the herbs can be ordered by the proportion of the total population eaten (Fig.4). Second, in

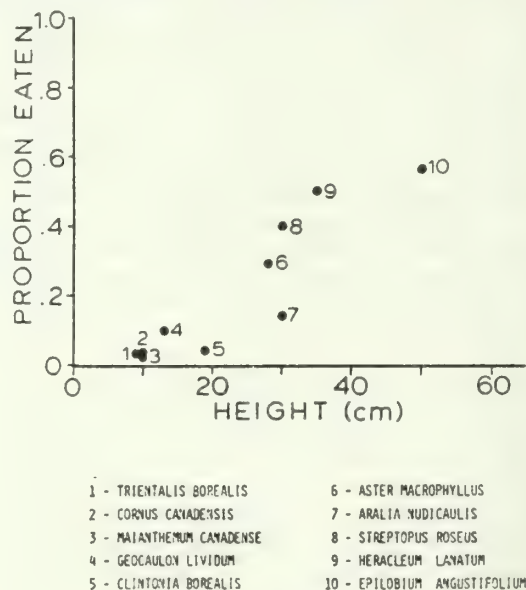


Figure 4.--Relationship between height and the proportion eaten for 10 herb species on Minong Island.

most cases, these preferences can be confirmed by pairwise comparisons. Table 1 summarizes the results of the pairwise tests, an example of which is shown in Figure 5. There were 8 pairwise tests where the two species being compared co-occurred and therefore a valid comparison could be made. In all 7 cases where the moose showed a clear preference between two species, the pairwise comparison corresponded with the ordering based on the proportion of the total population eaten. For the last case, the comparison between *Clintonia borealis* and *Geocaulon lividum*, the pairwise test indicated no preference (i.e., for those quadrats analyzed, the plants are eaten in proportion to their relative abundance). However, the proportion method indicates *G. lividum* (10% eaten) should be preferred to *C. borealis* (4% eaten). However both are low preference food items and the low proportion of *C. borealis* eaten is probably be-

C. borealis is more common and is situated on the northwestern side of the island, an area not frequented by moose (Peterson 1978).

1.--Summary of preferences between pairs of herb species. A + indicates that moose prefer the plant in the column to the one in the row. A - indicates that insufficient data were available to determine preferences between the two species. A = indicates that no clear preference was shown.

	<u>A. macrophyllus</u>	<u>A. nudicaulis</u>	<u>C. borealis</u>	<u>G. lividum</u>	<u>M. canadense</u>	<u>T. borealis</u>	<u>C. canadensis</u>
<u>A. macrophyllus</u>							
<u>A. nudicaulis</u>	-						
<u>C. borealis</u>	-	+					
<u>G. lividum</u>	+	-	=				
<u>M. canadense</u>	-	+	+	-			
<u>T. borealis</u>	-	-	-	-	-		
<u>C. canadensis</u>	+	+	-	+	-	-	

on both ranking methods, *Aster macrophyllus*, *A. nudicaulis*, *Streptopus roseus*, *Heracleum* and *Epilobium angustifolium* were considered reference herbs (herbs 1) and *Trientalis borealis*, *Cornus canadensis*, *Maianthemum canadense*, *G. lividum* and *Clintonia borealis* were considered low preference herbs (herbs 2). Similarly, on previous studies, the shrubs were divided into high preference (shrubs 1) and low preference (shrubs 2). The choice of food items by moose reflects differences in the nutrient quality of the food. Leaves of herbs and deciduous trees and shrubs have the highest nutrient values and are easier to digest than woody tissues or old leaves (see Peterson 1983 for a detailed list of references). The diets of moose are essentially maintenance diets (Peterson and Davis 1973); most malnutrition occurs in late winter (Peterson 1977). In addition, moose appear to maximize bite size. They select tall herbs to short herbs (Fig.4) and prefer shrubs to herbs. Moose can eat shrubs more efficiently since they can strip the leaves from entire

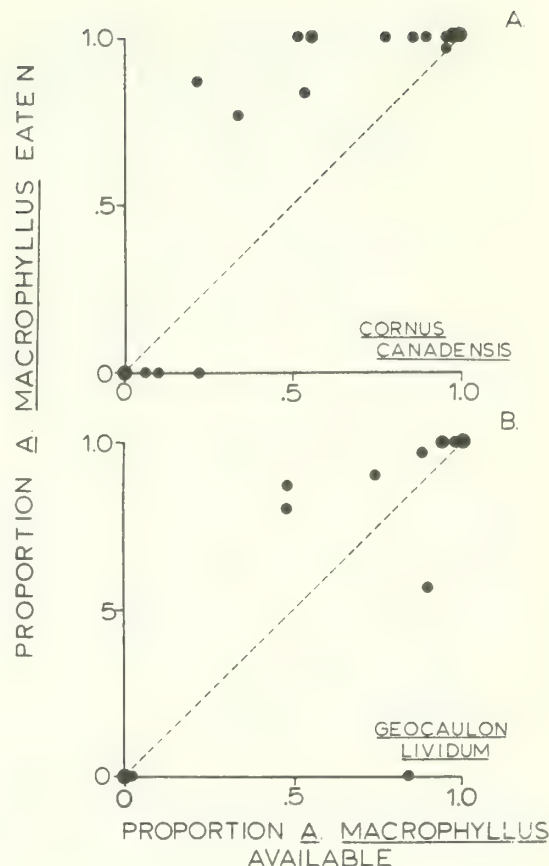


Figure 5.--Examples of pairwise comparisons showing preference relationships between *Aster macrophyllus* and *Cornus canadensis* (A) and between *A. macrophyllus* and *Geocaulon lividum* (B). See Table 1 for a summary of the results from the pairwise comparisons. Proportion of *A. macrophyllus* available = number of *A. macrophyllus* shoots in the quadrat/number of shoots of both species being compared. Proportion of *A. macrophyllus* eaten = number of eaten *A. macrophyllus* shoots/number of eaten shoots of both species.

branches; for herbs, only a few shoots can be eaten in one bite.

Availability of plant foods

Foods are available at different times of the year depending on the location. Data from the permanent transect indicate that plants leaf first on the ridges of the main island and last along the shoreline and on the small islands (Fig.6).

Predicted feeding pattern

The food preferences of moose and the availability of plant foods can be used to predict the feeding patterns of moose. Since

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WATER TRANSPORT IN SOIL AND ROOTS: INFLUENCE OF ROOT PROPERTIES ON WATER UPTAKE¹

Susan J. Riha and Mary Ann Levan²

Abstract.— An analog is used to predict the effects of changing root density and root resistance on the ability of stands of trees to maintain potential transpiration rates as the soil dries. Increasing root density and decreasing root resistance can increase water uptake, especially when the soil is moist. However, in these simulations, after an extended period of no rainfall, there was little difference in transpiration rate between high and low root density or root resistance stands.

Water moves in response to a potential gradient from the soil into plant roots, through the vascular system of the plant and into the vapor phase, through stomates into the air. An analog model, first proposed by Peter Honert (1948), in which soil and plant resistances are considered in series, has generally been used to describe this movement of water. Using this approach,

$$E = \frac{\psi_s - \psi_l}{R_s + R_r + R_x + R_l} \quad (1)$$

E is the rate of water flow from the soil to the plant leaf ($\text{kg m}^{-2} \text{s}^{-1}$); ψ_s and ψ_l are the water potentials of the bulk soil and the leaf, respectively, (J kg^{-1}); and R is the resistance to water flow ($\text{m}^4 \text{kg}^{-1} \text{s}^{-2}$) in the plant continuum. This overall resistance is a series combination of soil (R_s), root (R_r), xylem (R_x), and leaf mesophyll (R_l) resistances to water flow.

When the rate of water flow into the plant equals the rate of water moving in the vapor phase through stomates into the atmosphere (transpiration rate), then the system is at steady state and actual transpiration should equal potential transpiration.

When the rate of water flow from the soil through the plant is less than the rate of water vapor moving out of the plant, then plant water content and hence potential must at least temporarily decrease. Decreases in plant water potential cause both direct and indirect decreases in plant growth.

Since the rate of water flow from soil through plants is considered to be controlled by a series combination of resistances, there has long been an interest in understanding these resistances, measuring them, and establishing their relative importance (Newman 1974). Soil resistance is considered the resistance to water flow from the bulk soil to the cortex of a cylindrical root. The equation used to calculate this resistance is derived from one by Gardner (1960);

$$\frac{q}{2\pi r l} = -k \frac{d\psi}{dx} \quad (2)$$

where q is the rate of water uptake (kg s^{-1}), r is the radius of the root (m), l is the length of the root (m), k is the hydraulic conductivity of the soil (kg s m^{-3}), ψ is the water potential of the bulk soil or root surface (J kg^{-1}), and x is half the mean inter-root distance (m), which depends on root density. Thus soil resistance is a function of both plant (root density and radius) and soil (the hydraulic conductivity) properties.

Root resistance is considered the resistance to water flow between the root cortex and xylem with the bulk of this resistance apparently located in the endodermis. In practice, root resistance (or its inverse, root conductance), is generally either calculated or measured as a property of the entire root system. Conductance is then considered directly proportional to root length, and partitioned through the profile according to the pattern of root density with depth.

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Water moves within the xylem after crossing the endodermis in the root and before entering the mesophyll in the leaf. This xylem resistance is usually considered small compared to the other resistances. The mesophyll resistance is the resistance to passage from the xylem into the mesophyll cells. Although this resistance is probably not as large as the root resistance, it may be of the same order of magnitude.

It has sometimes been assumed that some measure of drought adaptation can be achieved by increasing root density and/or decreasing root resistance, thereby increasing water uptake from the soil. Root system parameters considered important to the pattern of soil water withdrawal from the profile are total root length and its distribution within the profile. Theoretically, both soil and root resistance depend on root density. Soil resistance is directly proportional to the mean inter-root distance, increasing as root density decreases. The partitioning of root resistance within the profile directly depends on the distribution of root density with depth.

The total root length to be partitioned through the profile is generally expressed as L_A , root length per unit of ground surface area. The range in reported values of L_A for woody species, grasses, and other herbs is surprisingly small (Table 1), with considerable overlap between plant groups. (Reported values for woody species do not include mycorrhizae.)

Table 1.--Root length per unit of ground surface (L_A) for selected plant groups

Plant group	Number of species examined	L_A (cm/cm ²)	Reference
Woody species	*	23 - 480	See Table
Gramineae	15	100 - 4000	Newman
Other herbaceous species	7	52 - 310	<u>Ibid.</u>

* Four individual species plus three mixed stands.

Although the L_A of woody species may vary by more than an order of magnitude, there are probably upper and lower limits not much outside this range which bracket all natural forests in which canopy closure has occurred. The data of Hopkins (Fig. 1) are typical of woody root systems, demonstrating the non-uniform density distribution with depth generally observed. Root density decreases rapidly, often exponentially, with depth, with most root length concentrated in the surface organic horizons.

Root system density is apparently controlled by both water and nutrient availability in the profile. Certain nutrients such as phosphorus move to roots by the relatively slow process of diffusion; uptake of such nutrients is greatly enhanced by increases in soil-root contact area. Uptake of nutrients such as calcium, which move to roots mainly by the relatively fast process of mass flow, is less affected by root-soil contact.

Table 2. Root length per unit of ground surface (L_A) for selected woody species

Stand Description	Age	Location	L_A	Reference
Spruce flat balsam fir, red spruce, red maple, yellow and white birch	mature	Adirondack Mts. USA	23	Hopkins, 1939
Good hardwood sugar maple, beech, yellow birch	mature	Adirondack Mts. USA	28	<u>Ibid.</u>
Poor hardwood red spruce, beech, sugar maple, yellow birch, red maple, hemlock	mature	Adirondack Mts. USA	43	<u>Ibid.</u>
Pear var. William Bon Chretien	20-40 y	Goulburn Valley Australia	26-69	Cockroft and Wallbrink, 1969
Douglas fir	36 y	Oxford England	77	Reynolds, 1970
Douglas fir	20 y	Vancouver Is. Canada	107	Nnyamah and Black, 1977
Scots pine	45 y	Thetford Chase England	126	Roberts, 1976
Jarrah (<u>Eucalyptus marginata</u>)	mature	Darling Range Australia	480	Carbon <u>et al.</u> , 1980

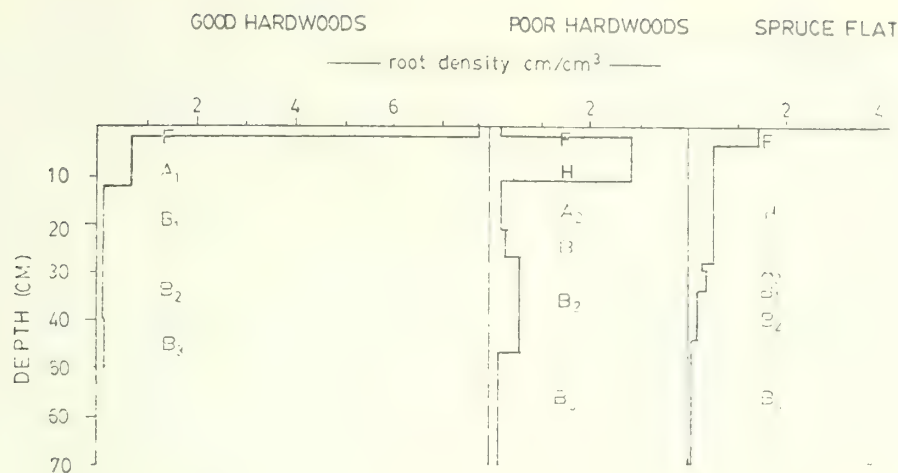


Figure 1. Pattern of root density with depth in three mature stands in the Adirondacks. Stand composition was as follows: good hardwoods - sugar maple, beech, yellow birch; poor hardwoods - red spruce, beech, sugar maple, yellow birch, red maple, hemlock; spruce flat - balsam fir, red spruce, red maple, yellow and white birch. After Hopkins 1939.

ably, high surface root density is a response to the almost exclusive occurrence of such nutrients as phosphorus in the organic layers, with lower subsoil densities adequate for uptake of mass-flow nutrients and water. This scheme implies that only relatively low root densities are sufficient for water uptake.

Field observation such as that just described suggests that dense root systems are not, however, generally produced in the soil volume supplying the bulk of the water to a stand. In addition, the interdependence of the quantity of water (or nutrient content) and resistance terms of the equations describing water flow, together with the nonlinear form of their relationship make it impossible to imagine the effect on water flow of a change in one of the parameters. For this reason, an analog model of the soil-plant-atmosphere continuum must be used to predict the effect on water uptake of changes in such parameters as root density and root resistance. In this approach, a set of equations describing water flow is solved iteratively in short time steps, constantly modifying the interdependent parameters in the equations, and arriving at a solution is impossible to obtain mentally. This approach can also indicate which properties of the system (such as soil water content) are most sensitive to changes in root parameters, and which are most easily measured.

The following is a brief description of the model. Initially, some potential daily transpiration is set (Table 3), and this is divided into hourly rates. The soil is divided into a series of layers (i), with different root densities assigned to each layer. Root systems with a depth of 28 or 280, with density decreasing

Table 3. Values used in model

Description	Value	Dimension
Soil (silt loam)		
Initial water content	0.25	m ³ m ⁻³
Bulk density	1.3	Mg m ⁻³
Saturated hydraulic conductivity	0.0003	kg s m ⁻³
Air entry water potential	-2.1	J kg ⁻¹
Empirical value from soil moisture release curve	4.2	-
Plant		
Total root length	280 or 28	cm cm ⁻²
Depth for 63% of roots	0.20	m
Root radius	0.001	m
Total root resistance	3×10^6 or 7.5×10^6	m ⁴ s ⁻¹ kg ⁻¹
Total leaf resistance	2×10^6	m ⁴ s ⁻¹ kg ⁻¹
Leaf water potential at which stomatal closure occurs	-1200	Pa
Atmosphere		
Potential transpiration rate	4	mm day ⁻¹

exponentially with depth were chosen for use in the model. The transpiration rate has to equal the sum of the water uptake rates for each of the soil layers:

$$E = \sum_i E_i = \sum_i \left(\frac{\psi_{xi} - \psi_{si}}{R_{si} + R_{ri}} \right) \quad (3)$$

The xylem water potential is then calculated by rearranging equation 3 (Childs et al. 1977). If the xylem resistance is assumed to be negligible, the leaf water potential can be calculated using the equation:

$$\psi_l = \psi_x - ER_l \quad (4)$$

Water moves within the xylem after crossing the endodermis in the root and before entering the mesophyll in the leaf. This xylem resistance is usually considered small compared to the other resistances. The mesophyll resistance is the resistance to passage from the xylem into the mesophyll cells. Although this resistance is probably not as large as the root resistance, it may be of the same order of magnitude.

It has sometimes been assumed that some measure of drought adaptation can be achieved by increasing root density and/or decreasing root resistance, thereby increasing water uptake from the soil. Root system parameters considered important to the pattern of soil water withdrawal from the profile are total root length and its distribution within the profile. Theoretically, both soil and root resistance depend on root density. Soil resistance is directly proportional to the mean inter-root distance, increasing as root density decreases. The partitioning of root resistance within the profile directly depends on the distribution of root density with depth.

The total root length to be partitioned through the profile is generally expressed as L_A , root length per unit of ground surface area. The range in reported values of L_A for woody species, grasses, and other herbs is surprisingly small (Table 1), with considerable overlap between plant groups. (Reported values for woody species do not include mycorrhizae.)

Table 1.--Root length per unit of ground surface (L_A) for selected plant groups

Plant group	Number of species examined	L_A (cm/cm ²)	Reference
Woody species	*	23 - 480	See Table 1
Gramineae	15	100 - 4000	Newman 1
Other herbaceous species	7	52 - 310	<u>Ibid.</u>

* Four individual species plus three mixed stands.

Although the L_A of woody species may vary by more than an order of magnitude, there are probably upper and lower limits not much outside this range which bracket all natural forests in which canopy closure has occurred. The data of Hopkins (Fig. 1) are typical of woody root systems, demonstrating the non-uniform density distribution with depth generally observed. Root density decreases rapidly, often exponentially with depth, with most root length concentrated in the surface organic horizons.

Root system density is apparently controlled by both water and nutrient availability in the profile. Certain nutrients such as phosphorus move to roots by the relatively slow process of diffusion; uptake of such nutrients is greatly enhanced by increases in soil-root contact area. Uptake of nutrients such as calcium, which move to roots mainly by the relatively fast process of mass flow, is less affected by root-soil contact.

Table 2. Root length per unit of ground surface (L_A) for selected woody species

Stand Description	Age	Location	L_A	Reference
Spruce flat balsam fir, red spruce, red maple, yellow and white birch	mature	Adirondack Mts. USA	23	Hopkins, 1939
Good hardwood sugar maple, beech, yellow birch	mature	Adirondack Mts. USA	28	<u>Ibid.</u>
Poor hardwood red spruce, beech, sugar maple, yellow birch, red maple, hemlock	mature	Adirondack Mts. USA	43	<u>Ibid.</u>
Pear var. William Bon Chretien	20-40 y	Goulburn Valley Australia	26-69	Cockroft and Wallbrink, 1969
Douglas fir	36 y	Oxford England	77	Reynolds, 1970
Douglas fir	20 y	Vancouver Is. Canada	107	Nnyamah and Black, 1977
Scots pine	45 y	Thetford Chase England	126	Roberts, 1976
Jarrah (<u>Eucalyptus marginata</u>)	mature	Darling Range Australia	480	Carbon et al., 1980

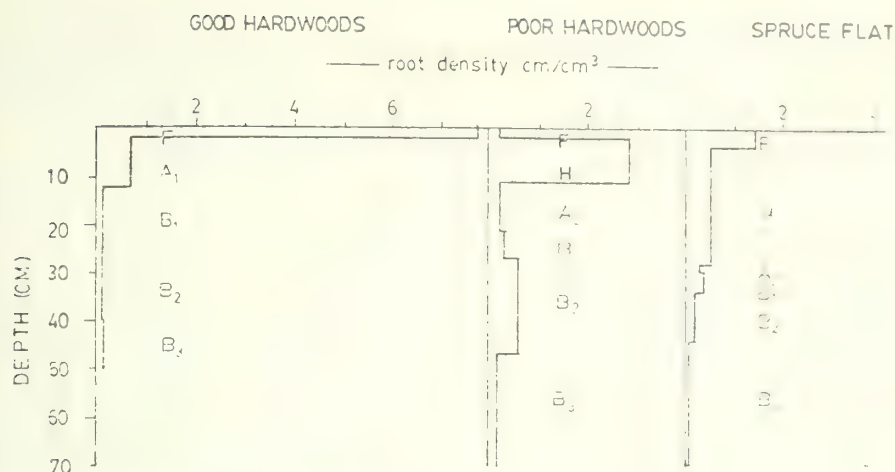


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Empirical value from soil moisture release curve	4.2	-
Plant		
Total root length	280 or 28	cm cm^{-2}
Depth for 65% of roots	0.20	m
Root radius	0.001	m
Total root resistance	3×10^6 or 7.5×10^6	$\text{m}^4 \text{ s}^{-1} \text{ kg}^{-1}$
Total leaf resistance	2×10^6	$\text{m}^4 \text{ s}^{-1} \text{ kg}^{-1}$
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$$\psi_l = \psi_x - ER_l \quad (4)$$

The leaf water potential is calculated by combining equation 3 and 4 to obtain:

$$\psi_l = \frac{\psi_{si}/(R_{si} + R_{ri})}{\sum_i 1/(R_{si} + R_{ri})} - E \left[R_l + \frac{1}{\sum_i 1/(R_{si} + R_{ri})} \right] \quad (5)$$

The first term on the right of the equation can be considered a weighted mean soil water potential, $\bar{\psi}_s$ (G. S. Campbell, personal communication). As the leaf water potential becomes more negative, stomatal resistance increases, thereby decreasing the actual transpiration rate below the initially assigned transpiration rate.

E_i , the amount of water uptake by roots in each layer of soil, is a sink term in the Richard's equation, which is used to calculate soil water flow between soil layers. The equation used to describe the relationship between soil water potential and soil hydraulic conductivity are given by Campbell (1974). The values used in these equations are specific to a soil and, in this model, they are assumed to be constant with depth (Table 3).

Model results are presented by plotting the ratio of actual to potential transpiration (E/EP) against the weighted mean soil water potential ($\bar{\psi}_s$) over time. Results of studies with *Pinus contorta* presented in this way (cf. Lopushinsky 1975) have shown that when the soil water potential becomes increasingly negative, transpiration decreases rapidly, reaching some constant low value. Model results follow this expected pattern (cf. Fig. 2 and 3). In this study, the model was used to compare stands of trees with comparatively low and high root densities, as well as root systems with low and high root resistances.

The model results presented in Figure 2 illustrate the effect of increasing rooting density an order of magnitude uniformly through the profile. For approximately the first 10 days, both higher and lower root density stands transpire at the maximum rate. In the next 10 days, actual transpiration falls below potential transpiration more quickly in the stand with lower root density. By 20 days, the stand with the higher density root system is transpiring slightly more than the stand with the lower root density. In addition, the soil of the higher root density stand has a lower mean soil water potential. At 40 days, actual transpiration is slightly higher for the stand with the lower root density, while the soil of the high root density stand still has a more negative soil water potential. Thus, increasing root density

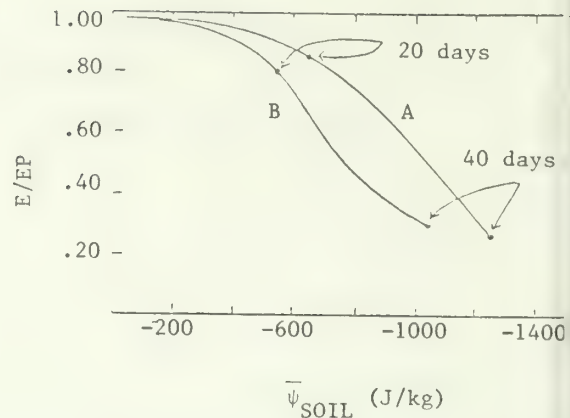


Figure 2. Effect of root density on relationship between actual transpiration and the weighted mean soil water potential over time. A - higher root density stand (280 cm²) B - lower root density stand (28 cm²)

tenfold resulted in only slightly increased water uptake. The total amount of stored water this represents is 5 mm, or slightly more than the potential transpiration rate for a single

The model results presented in Figure 3 illustrate the effect on water uptake of increasing root resistance by 250%. Increasing root resistance decreases the transpiration rate the stand achieves even under well-watered conditions. On the twentieth day after rain, the stand with the lower root resistance is transpiring close to a maximum although the mean soil water potential for both stands is similar. By day 40, transpiration rates of both stands are similar and less than 30% of maximum, while $\bar{\psi}_s$ of the stand with the higher root resistance is slightly less negative than that with the lower root resistance. These effects are predicted by the model mainly because, for a given transpiration rate, the stand with the higher root resistance attains more negative leaf water potentials than that with lower root resistance. If the relationship between leaf water potential and stomatal resistance remains the same for both stands, in the stand with the higher root resistance E/EP will decrease sooner due to increasing stomatal resistance. This remains the case if the weighted mean soil water potential approaches the critical leaf water potential.

Table 4 presents the model predictions of soil water potential and soil water content at 2 days and 3 depths at high and low root densities. Enhanced water uptake from the soil effected by changes in root density and distribution would be difficult to detect. According to model predictions, there would be no measurable difference at day 10 between the high and low root densities.

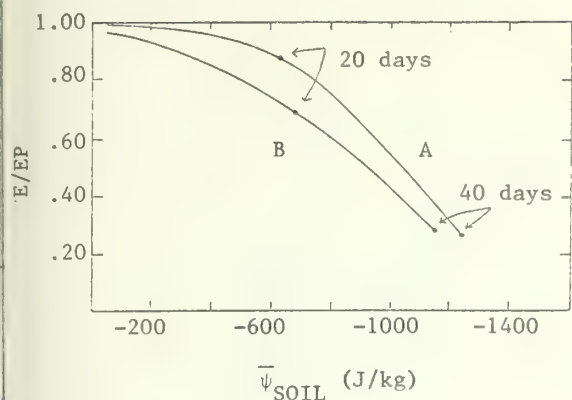


Figure 3. Effect of root resistance on the relationship between actual transpiration/potential transpiration and the weighted mean soil water potential over time. A - root system with lower resistance ($3 \times 10^6 \text{ m}^4 \text{ s kg}^{-1}$); B - root system with higher resistance ($7.5 \times 10^6 \text{ m}^4 \text{ s kg}^{-1}$).

ils and only slight differences in the surface cm at day 30. The model predicts that there would be differences between the higher and low-root density stands in the predawn and midday leaf water potentials by day 30 (Table 5).

Table 4.--Comparison of predicted soil water potentials and soil water contents under low and high root density stands

Day	Depth cm	Low root density		High root density	
		ψ_{soil}	Soil water content	ψ_{soil}	Soil water content
		J/kg	cm^3/cm^3	J/kg	cm^3/cm^3
0	0 - 27	-300	.16	-300	.16
	27 - 53	-150	.19	-150	.19
	53 - 80	-60	.23	-60	.23
30	0 - 27	-1060	.12	-1100	.11
	27 - 53	-940	.12	-1090	.12
	53 - 80	-430	.14	-680	.13

Table 5.--Comparison of predicted predawn and midday leaf water potentials of low and high root density stands

Predawn ψ_{leaf}		Midday ψ_{leaf}	
Low root density	High root density	Low root density	High root density
-210	-210	-730	-720
-850	-1000	-1590	-1310

Model simulations: have shown that increasing root density and decreasing root resistance do lead to increases in stand water uptake. It is difficult to evaluate, however, whether changes in the quantity and pattern of water uptake lead to increased stand survival and productivity.

Increasing root density and decreasing root resistance result in maintenance of higher transpiration rates for a longer period. However, this increased depletion of soil water in turn causes soil water potential to be more negative. These stands then must establish lower leaf water potentials to maintain a gradient for flow.

In addition, production and maintenance of roots, decreases in leaf water potential, and increases in stomatal resistance all involve energy expenditures which must be balanced against the energy gains resultant from improved water status of the stand.

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IMPACT OF FUSIFORM RUST ON LOBLOLLY PINE PLANTATIONS¹

Kathleen E. Moore²

Abstract.--An individual tree growth model (PTAEDA) developed at Virginia Polytechnic Institute was modified to reflect the effects of fusiform rust infection. The data base for rust effects was a heritability study in a high hazard area for rust. Mortality, growth loss, and product quality loss for individual trees are all strongly affected by the year after planting in which infection takes place.

INTRODUCTION

Fusiform rust is a serious disease of loblolly and slash pines under plantation management. The causal organism, *Cronartium fusiforme*, produces galls on the branches and main stem of the pine host. Mortality, growth loss, and product degradation are the major categories of loss.

Construction of impact models for plant diseases has been left chiefly to plant disease epidemiologists. The importance of these models to the manager of a crop should be obvious: an objective means of evaluating management alternatives under different disease conditions is essential. The uses of impact models extend also to the evaluation of control measures and genetic selections. The aim should be to reduce impact, not just the amount of disease.

A dialogue between growth and yield modelers and forest pathologists is necessary in part because the quantification of gain from various management alternatives can sometimes be a different process than the quantification of loss. The difference is a function of the individual's purpose in constructing the model. Models designed to demonstrate gain do not give accurate results when they are used to model loss.

Prediction of disease loss requires the integration of models of disease development,

stand development, and impact -- all of which share a complex set of relationships with time. Time is something the forest manager must understand well; the perception of time on the part of the forest manager distinguishes him/her from the managers of other crops. Study of the impact of fusiform rust illustrates these concepts; both the problems and benefits associated with impact modeling are demonstrated.

The objective of the research reported here was to develop a model of impact of fusiform rust on yields from loblolly pine plantations that could be used by forest managers to evaluate management alternatives, based on an early assessment of the disease. The approach taken was to modify a pre-existing growth and yield model for loblolly pine, using data on rust and growth from a heritability study.

ANALYSIS OF THE DATA BASE

The data used were the first 10 years' measurements of 9600 trees in the loblolly pine heritability study. Some detailed data on individual galls were also taken at age 17. Details of the study are available in Stonecypher *et al* (1973). The study is located in a high rust-hazard area in South Georgia. There are six replications in the planting design, three at each of two locations. The two locations differed in the amount of rust that was present: one location experienced approximately 20% incidence of stem infection, while in the other as many as 65% of the trees in one rep had stem infections by age 5.

Mortality was the first category of impact explored. The relationship (regression) of rust-associated mortality (RAM) at age 10 with percent stem-infected at earlier ages revealed that there is a difference in the

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slope of the regression lines using the age 3 percent-infected as the predictor versus using the age 5 percent-infected. A higher proportion of trees infected at age 3 die by age 10 than those infected at age 5. This result confirms published results of Wells and Dinus (1978).

This led to the hypothesis that the probability of an individual tree dying of rust was strongly affected by the year in which it became infected. A non-linear relationship, in which probability of mortality declines steeply with age-at-infection, describes this trend (Fig. 1).

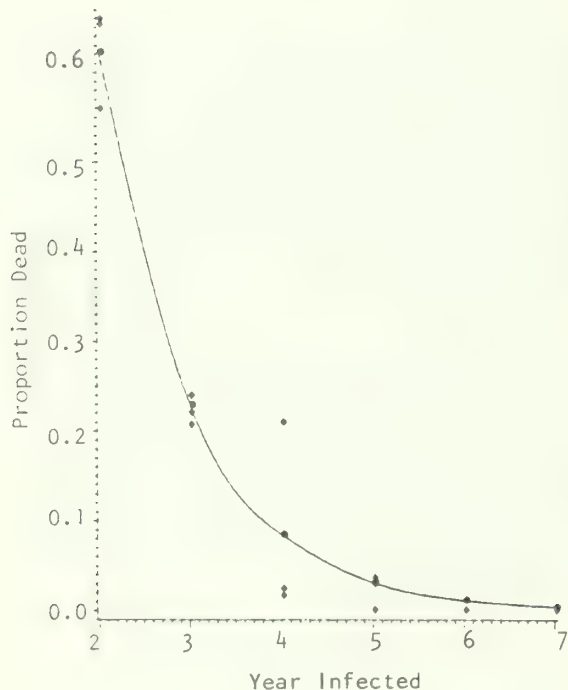


Figure 1.--Exponential decline model for relationship of proportion dead (rust-associated mortality) with year infected.

The second category of impact is individual-tree growth reduction. Here too, age-at-infection is a significant factor. Trees infected by age 3 are smaller at age 10 than those infected at age 5, but not age 3. Infected trees may have 15-20% less volume at age 10, if they were infected early.

The effects of rust, while dramatic for many trees, are apparently minimal for others, in terms of effects on mortality and growth. The result is that at age 10 in the heritability study, many infected trees occupied

good competitive positions in the canopy, indicating that this population of loblolly pine has a substantial degree of tolerance the disease. This also implies that many infected trees have a good chance of survival to rotation when higher-value products, such as plywood (which are more severely affected by rust galls) are the expected return.

Height of the gall on the stem is also related to the year in which infection takes place, because the rust fungus infects the new shoots of the tree each year.

MODIFICATIONS TO THE MODEL

An individual tree growth model, "PTAE" which was developed by Richard Daniels and Harold Burkhart at V.P.I. (1975) was modified to reflect the effect of fusiform rust, based on an analysis of the heritability study data. This model, as it was originally constructed, "grows" a stand of trees to the end of the juvenile phase by using a series of regression equations describing how height and mortality are related to the input variables, i.e., site quality, planting density, site preparation, etc. Following the juvenile period, each tree is grown individually, year by year, based on an assessment of its competitive position. At any specified time in the life of the stand, stand summaries as well as a detailed "snapshot" of each tree can be produced by the model.

The model was modified in the following ways:

1. Fusiform rust is input as a disease progress curve -- the incremental amount of rust (percent stem-infected) in each year following planting, through age 8. Each tree is randomly assigned an infection-year on the basis of this input.
2. Mortality is assigned to each tree randomly based on the probability of mortality associated with the year in which the tree became infected.
3. A separate diameter distribution for trees infected by age 3 but which survive to age 10, is calculated.
4. Gall height and length at age 10 are determined for each surviving infected tree, again using year-infected as the predictor.
5. The option of selectively thinning rust-infected trees to achieve a specified basal area was added.
6. The degree of spatial aggregation of infected trees can be specified. This

was accomplished with a method similar to that described by Daniels et al (1979) in a seeded-stand simulator.

A measure of solid-wood products loss was obtained when a bucking and sawing program was interfaced to PTAEDA; logs are bucked above any rust gall on them.

RESULTS AND DISCUSSION

The individual tree model format of AEDA has made it a useful tool for exploring the impact of fusiform rust. This format allowed the incorporation of mortality, growth loss, and product degrade information to the model, as well as ready modification for selective thinning and manipulation of the spatial pattern. The results beyond the juvenile stage, however, are not verified and therefore should be regarded as simulation.

The model, because it is dependent on a competition index calculated on inter-tree distances, is sensitive to reductions in stand density. Individual trees respond to the decrease in competition by growing faster. This aspect of PTAEDA would appear to exaggerate tree growth at the lowest stand densities.

Nonetheless, the following general results were obtained with simulations of a wide range of rust progress curves:

Over longer rotations (up to 35 years), losses in standing volume may be ameliorated through increased growth of individual trees. This is essentially a thinning effect, and requires verification.

Most volume losses are from thinnings, because of the above-mentioned amelioration in standing volume over time.

Because many infected trees are projected to rotation, most financial loss could be from product degrade, depending on the objectives of management. With the bucking and sawing scheme in this model, there is a loss of both lumber volume and grade.

In the first 15 years, volume losses are 5-20% of the volume from uninfected stands, depending on the shape of the disease progress curve. Some results of rust-modified PTAEDA output are given in Table 1.

Comparisons of the projections to age 15 with published estimates from stand models (Lance et al 1981, 1982) indicate that these losses are comparable, given that slash pine appears to be more sensitive than loblolly to fusiform disease.

Table 1.--Average height, diameter, and cubic-foot volumes resulting from simulations of thinned plantations under different rust progress curves. Simulated planting density, 680 stems/acre with a site index of 60.

	Rust Infection ^a , %		
	0.0	34	54
Age 8:			
Height, ft	17.5	16.8	16.9
Diameter, in.	4.3	3.9	3.9
Volume, ft ³	753	488	415
Age 16:			
Height, ft	38.5	40.3	41.4
Diameter, in.	6.4	6.6	7.2
Volume, ft ³	1,790	1,576	1,532
Thinned Vol. ^b , ft ³	841	728	632
Age 25:			
Height, ft	59.8	61.2	60.4
Diameter, in.	11.7	12.1	12.2
Total Vol. ^c , ft ³	4,953	4,725	4,576

^aTotal percent stem infection through age 5, weighted by probability of mortality for each infection-year.

^bRow thinning.

^cStanding volume + thinned volume.

RELATIONSHIP BETWEEN LOSS AND DISEASE

There are several ways of expressing the relationship between an early assessment of disease and the final yield of crop. It is important to find the type of expression that reflects the particular dynamic of disease and host that is of interest.

In this case, it is clear that any prediction of yield loss in the future has to take account of the age-dependency of impact. The spatial pattern dependency may also have to be taken into account. Since mortality appears to be the largest factor in impact on total volume production, a measure of disease that is based on percent stem-infected at ages 1 through 5 weighted by the probability of mortality associated with each year, was constructed. A linear relationship resulted.

The relative magnitude of the various impacts that rust may have on yield depends upon the management of the stand and the products expected from that management regime. For instance, in shorter rotation pulpwood-only stands, rust impact on final standing

volume would be the primary impact. Longer rotations in which a whole range of products is expected would be subject to the whole range of possible impacts.

Finally, fusiform rust losses alone have to be put in perspective with other sources of loss, and with interactions between rust and those other sources of loss. For instance, rust-infected stands are apparently at a higher risk to wind damage, since severe galls may weaken the stem. Also, insect attack may be more frequent or severe in rust-infected stands, and fire is a greater threat to rust-galled trees.

ACKNOWLEDGEMENT

The author wishes to acknowledge the programming skills of Mr. Bruce Roman, who made the initial modifications to PTAEDA for International Paper Company.

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DENDROCHRONOLOGY AND FOREST PRODUCTIVITY: RED SPRUCE

WOOD DENSITY AND RING WIDTH IN MAINE¹

Laura E. Conkey²

Abstract.--Dendrochronology, using both ring widths and wood densities, can be employed in assessing environmental influences on forest productivity. Growth patterns in three red spruce stands in Maine indicate, spatially and through time, a varying record of response to climatic and other natural or human-induced perturbations.

INTRODUCTION

Forest productivity is measured in terms of not only volume of wood obtained, but also wood quality, especially with regard to fiber strength and wood density. Dendrochronology, the study of precisely dated, yearly increments of growth, has most frequently been concerned with wood quantity, with width measurements of the early tree rings. In areas of extreme climate, the strong relationship between the pattern of such width measurements and the pattern of climatic events, such as rainfall or temperature, has permitted the accurate crossdating of wood samples as well as the reconstruction of past climatological events (Stockton and Meko 1975; Fritts 1976). In more temperate regions of the world, such as northeastern North America, where climate - tree-growth correlations are less strong, results of dendroclimatological reconstructions using ring widths appear to be less reliable. A recently developed technique, x-ray densitometry (Lenz et al. 1976; Schweingruber et al. 1978), produces series of yearly wood density values that have been shown to have strong links to climate, especially in more temperate regions (Conkey 1979; Schweingruber et al. 1979). In New England, in particular, peak or maximum latewood density values of red spruce (*Picea rubens* Sarg.) facilitate the crossdating procedures neces-

sary to such work, and show high correlation to growing season temperatures as well as to other spring and summer climatic conditions (Conkey 1982). Thus, long time series representing both wood quantity (tree-ring widths) and wood quality (tree-ring densities) are obtainable on a year-by-year basis, and can be examined for evidence of climatic and other environmental effects on tree growth.

The effect of climate on tree growth is perhaps most easily estimated statistically by comparing accurately dated ring widths or densities to yearly or seasonal climatic data which are believed to be related to physiological aspects of growth. Up to 100 years of climatic data may be available for such comparisons, and can form the basis for dendrochronological reconstructions of climate for the 200 to 300 years (or more) of the tree-ring record (Fritts 1976; Conkey 1982). Other environmental factors may also be compared to tree growth: the effect of fire or its exclusion (Sutherland in prep.), air pollution events (Thompson 1981), and insect damage (Schweingruber 1979) have all been documented in patterns of tree-ring widths or densities (Sutherland in press).

The purpose of this paper is to show how yearly patterns of wood quantity and density can indicate climatic and other environmental influences on forest productivity. A comparison of the width and density series can delineate differences in response to environmental phenomena between the two growth indicators. Both temporal and spatial perspectives are incorporated, by examining 200- to 300-year long time series of ring widths and maximum latewood densities from three red spruce sites spanning 200 km of the mountain front of Maine.

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Tree cores were extracted from 15 to 19 red spruce trees from each of three sites located along the mountains of Maine (Table 1): Elephant Mt. in western Maine, Sugarloaf Mt. near Kingfield, and Traveler Mt. in Baxter State Park. All three sites are above 900 m elevation and are representative of the highest elevation stands of red spruce in this region. The cores were prepared and analyzed densitometrically at the Swiss Federal Institute of Forestry Research, Birmensdorf, Switzerland. They were first carefully sawn to 1.2 mm thickness, acclimated to constant hygroscopic conditions, and then they were x-rayed. A narrow beam of light was then passed through the developed x-ray film, ring by ring, and the brightness was recorded. The measured densities were calibrated to represent actual wood density. Total ring width and maximum latewood density for each yearly ring were recorded mechanically, as well as minimum earlywood density, earlywood width, and latewood width, which were used in other studies (Conkey 1982). Each parameter was carefully crossdated among all core series to assure exact dating

(Stokes and Smiley 1968). Standard dendro-chronological practice involves standardization of the core series to remove biological growth trends and age effects (Fritts 1976); this was done in preparation for the climatological analyses, which can be negatively influenced by growth trends. The original core series of ring widths and maximum densities were also individually averaged without standardization, for use in assessing non-climatic influences on growth.

Several tests of association were calculated among the width and density averaged series, including the Pearson product-moment correlation coefficient, correlation of first-differenced series, and the two-way chi square (χ^2) test of contingency tables (Nie et al. 1970; Gordon 1980; Conkey 1982). The first correlation coefficient indicates the degree of coherence integrated over all frequencies, measuring both the number of cases which agree between two series as well as the relative degree of correspondence. The coefficient is quite sensitive to long-term trends in one or both series. The effect of such trends may be eliminated by taking the first differences

Table 1.--Collection site descriptions and locations.

Site name, Chronology length and depth	Geographical location, map reference	Geological characteristics	Site description
<u>Elephant Mt.</u> 1667-1976 17 trees sampled, 32 cores used in final chronologies	44° 46' N 70° 46' W Franklin Co., Oquossoc quadrangle. Elevation 3000' - 3100' (915-945 m) ENE slope, 5°-10°	Granitic base, little soil development, largely humus. Within drainage of Swift - Androscoggin Rivers.	Relatively flat, hummocky area; spruce are tall, with medium to thick species density, foliage restricted to high branches. Other species include: <i>Betula</i> sp., <i>Oxalis montana</i> , <i>Abies balsamea</i> , ferns and mosses. Relatively open stand below canopy. <i>Picea rubens</i> clearly dominant.
<u>Sugarloaf Mt.</u> 1776-1976 19 trees sampled, 34 cores used in final chronologies	45° 02' 30" N 70° 19' W Franklin Co., Stratton quadrangle. Elevation 3600' (1097 m) NE slope, 35°	Igneous base, gabbro/diorite, with sandy solifluction deposits. Thick humus material, soil depth uncertain. Within drainage of Carrabassett - Kennebec Rivers.	Steep, exposed slope, partially cleared for ski trails, rest is densely wooded with much fallen dead wood. Proportion of spruce is low, most young growth is fir. Other species include: <i>Abies balsamea</i> , <i>Betula papyrifera</i> , <i>Oxalis montana</i> , mosses. <i>Abies</i> is dominant with the older <i>Picea</i> .
<u>Traveler Mt.</u> 1728-1976 15 trees sampled, 26 cores used in final chronologies	46° 04' 30" N 68° 51' W Piscataquis Co. Traveler Mt. quadrangle. Elevation 3050' - 3200' (930-975 m) NNW slope, 10°-20°	Traveler rhyolite base, hummocky humus cover, close to bedrock. Within drainage of the East Branch of the Penobscot River.	Moderate slope, close to summit of burned-over peak. Spruce density moderate, greatly inter- spersed with similar-size fir. Few very old specimens. Lots of downed trees, and open areas with dead standing snags. Other species include: <i>Abies balsamea</i> , <i>Betula</i> sp., thick ground cover of raspberry, ferns, clintonia, bunchberry, sorrel.

both series ($X_i - X_{i-1}$), and recalculating the correlation. This first-differenced correlation coefficient thus emphasizes the high-frequency degree of correspondence between two series. Finally, the χ^2 contingency analysis is conducted in order to indicate the existence and strength of any non-linear relationship between two series, a relationship which might produce low values of correlation. Whereas the significance of the χ^2 statistic indicates the presence of a relationship, its nature (linear or curvilinear) is revealed only by examination of the contingency table itself. The application of such tests of association help define the similarities and differences from one tree-ring site to another as well as the degree of correspondence between wood quantity (width) and wood quality (density) at each site.

RESULTS AND DISCUSSION

Statistical tests of association

An important criterion for dendrochronological analysis of tree samples is that the visible ring patterns of growth be similar enough from one tree to another and one site to another to allow exact calendar years to be assigned to each ring; such correlation is due to regional environmental similarities, mainly climate. Examination of test results among the ring-width variables from the three spruce sites in Maine (Table 2, top) indicates that significant site-to-site correlation does indeed exist for this growth variable. High-frequency correlation ("r-1" in the table) is also significant, and is higher than the correlation at all frequencies ("r"), indicating the existence of long-term trends in each series that are site-specific, compared to the year-to-year variations of width. Standardization of the series would, theoretically, remove unreplicated trends in the data that are due to uneven ages represented here in the averaged series. Results of the χ^2 analysis support the existence of statistical coherence among widths from one site to another, and linearity is inferred for all except the Traveler/elephant comparison, where the higher χ^2 value relative to the r value may imply a somewhat curvilinear pattern to the relationship.

Maximum density test results (Table 2, bottom) show increases in every test and every site comparison over the ring-width results. There is still an indication of similar long-term trends from one site to another, seen in the increase of r-1 values over the r values, but strong coherence at

all frequencies is suggested by the high values for all three tests. Clearly, the regional similarity of maximum density values is strong, and implies a strong macroclimatic control on latewood density.

Ring widths and maximum densities relate less well to each other at each site (Table 3) than they do among themselves from site

Table 2.--Tests of association^a of the averaged series of maximum density and ring width among three sites in Maine.

Width	r	r-1	χ^2
SUG/TRV (201)	.346	.518	41.79
SUG/ELE (201)	.456	.602	86.28
TRV/ELE (249)	.230	.502	51.45
Density	r	r-1	χ^2
SUG/TRV (201)	.547	.748	115.88
SUG/ELE (201)	.573	.726	101.32
TRV/ELE (249)	.648	.776	137.26

^aSample size in parentheses. SUG = Sugarloaf TRV = Traveler ELE = Elephant
r = correlation
r-1 = correlation of first differences
 χ^2 = 2-way chi square contingency table test
All test are significant at $p \leq 0.05$.

Table 3.--Tests of association^b between maximum density and ring width averaged time series at each of three sites in Maine.

	r	r-1	χ^2
Sugarloaf (201)	.186	.240	22.49 NS
Traveler (249)	.195	.235	27.07
Elephant (310)	.307	.218	40.24

^bTests and symbols as in Table 2.
NS indicates lack of significance, $p \leq 0.05$.
All other results are significant.

to site, indicating that the two growth parameters, while apparently influenced by macroclimate to varying degrees, do show differing responses to environmental stimuli. Large rings often exhibit lower overall specific gravity; thus wood quantity and wood quality are, generally, inversely related. The positive correlation between ring width and maximum latewood density seen here (Table 3) implies that the environmental stimuli affecting quantity and quality of wood may not be dissimilar, but that the actual physiological response may differ, perhaps in timing or duration.

Width and density averaged series

Macroclimatic influences on growth are evidenced both by the results of the tests of association, and by regression analyses in

which the widths and densities were used to predict growing season temperature, producing explained variance values of up to 0.47 (Conkey 1982). There remains much in the width and density variation, however, that does not appear to be climate-related, but instead implies the influence of other more site-specific or non-climatic environmental phenomena.

Figure 1 is a composite plot of unstandardized values of ring widths, averaged year by year at each site. Total average ring width for each year is visually broken down into earlywood and latewood portions, indicating both the relatively small proportion of red spruce wood that is considered "latewood" (between each set of plotted lines), and the resulting very stron

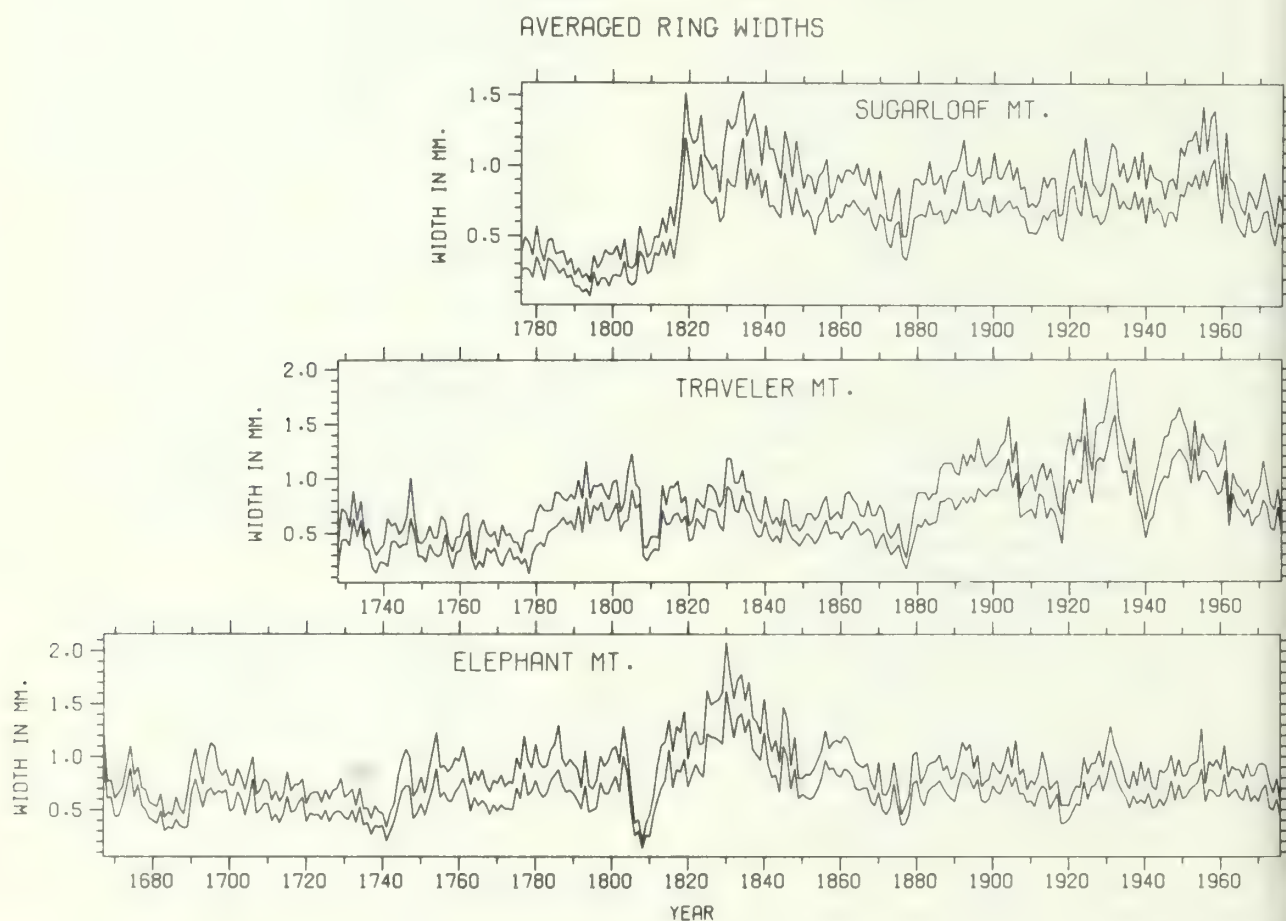


Figure 1.--Averaged ring widths (in millimeters) from three red spruce sample collection sites: Sugarloaf Mt. (top), Traveler Mt. (middle), and Elephant Mt. (bottom), Maine. Within each site plot are averaged total ring widths (upper line in each case) and averaged earlywood widths (lower lines); the distance between the two plotted lines is equal to the latewood width for each year.

similarity between earlywood and total ring widths. Patterns of growth suppression (narrow rings) and release (wide rings) are evident, both individually and in synchrony among the three sites, indicating regional and site-specific changes in forest productivity through time.

Those patterns in synchrony, both at high and low frequencies, include narrow rings in 1740, wide rings by 1830 with a gradual decrease until the late 1870s. All three sites show an abrupt growth decrease in 1917-18, and marked period of lower growth in the last two decades of record. Many of these patterns may be climatically controlled; the most recent growth decrease does appear, for instance, to follow a marked decline in spring temperatures at nearby climatic stations (Conkey 1982). A gradual warming during the last decades of the 19th century (Willett 1950) may also be reflected in the increase in ring widths after the late 1870s.

Maximum density variations can be seen in figure 2. The series in general show much less long-term trend than the ring-width series, as well as a greater variation on a year-to-year basis, in an oscillating fashion. Like the ring widths, however, many patterns of the densities can be traced from one site to another, indicating again the strong influence of regional climate on wood density. These are mostly of a high-frequency nature, with individual years standing out: 1740, again, with low density, and a jump from high to low in 1815-1816, high in 1831, 1841, 1846, 1870, and low in 1888, 1917, and 1954-56. Many of these relate to known events of a climatic nature, such as the cold spring and summer of 1816, and the cool-warm-cool pattern in 1954-56.

Some of the synchronous patterns, and, presumably, all of the non-synchronous ones, may be influenced by environmental events other than macroclimate. These may be best understood by examining both the width and

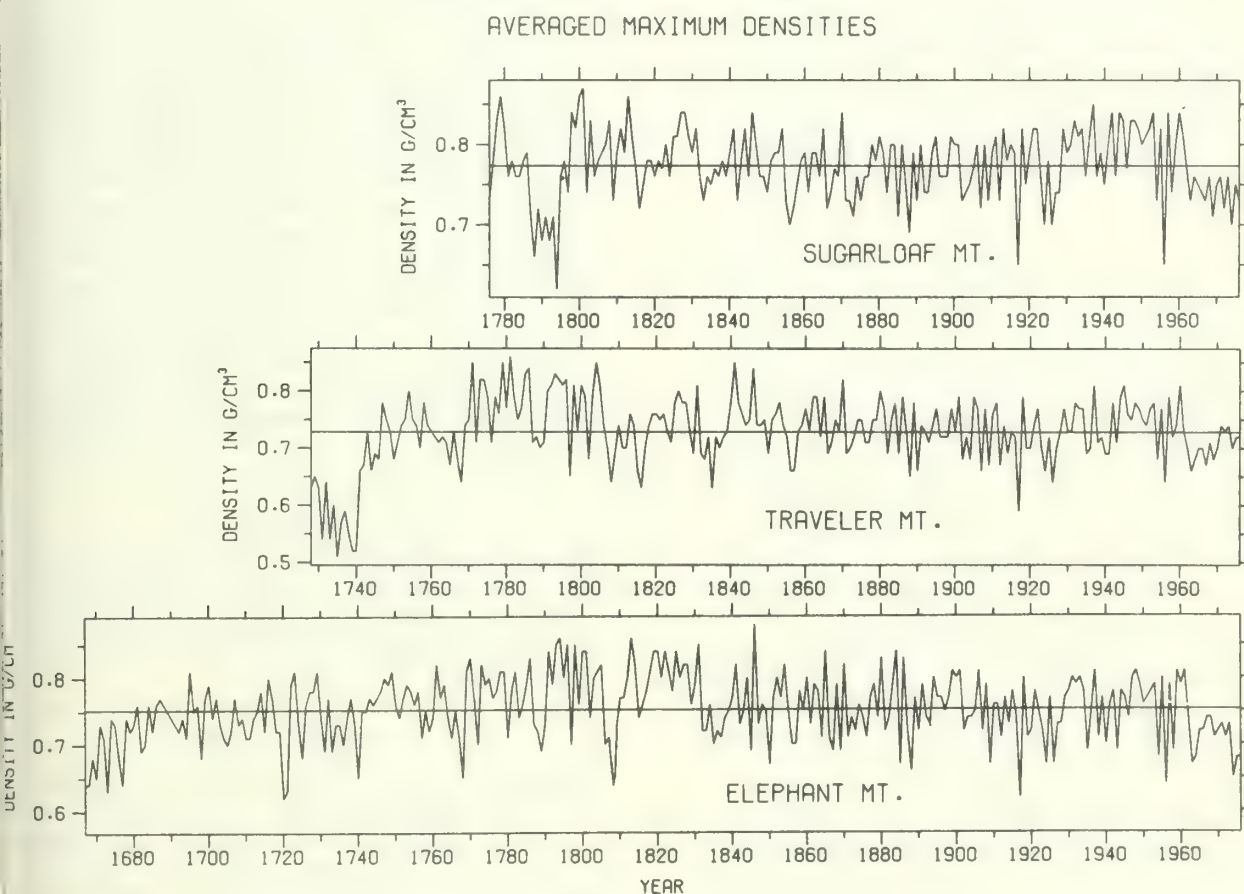


Figure 2.--Averaged maximum density values (in grams per cubic centimeter) from three red spruce sample collection sites: Sugarloaf Mt. (top), Traveler Mt. (middle), and Elephant Mt. (bottom), Maine. A horizontal line in each case represents the mean of each complete series.

density variations together. For instance, Traveler and Elephant show a marked ring-width decrease in 1808, with a one-year decrease in density as well. Ring widths at both sites, however, remain suppressed for several years. Such a pattern may indicate an insect infestation as seen from affected but surviving trees, with a ring-width suppression of several years duration, but a very quick return to mean density levels once the infestation peaks (Schweingruber 1979). The Sugarloaf site may not have been affected; or, conversely, it may have been cleared out of older individuals in that infestation, reducing the competition for light and nutrients for the young trees that grew underneath, and contributing to the surge in growth there after 1810. Many new trees enter the averaged series at this point at all three sites; this too may indicate canopy opening. Much of Maine was hit by a spruce budworm attack from 1912 to 1920, affecting spruce as well as fir; again there is a one-year low maximum density (1917), and a several-year ring-width decrease and slower return to mean values. At Traveler Mt. there is a marked increase in ring widths after this time, perhaps indicating an opening canopy. The only historically documented fire that I am aware of occurred near Traveler Mt. in 1903 (Anderson 1979); it is not clear from the width or density record that the sampled stand was directly affected by it.

The abrupt growth decrease at Traveler in 1940, however, is more elusive. It is not reflected in deteriorating climatic conditions (Conkey 1982), nor is the pattern repeated at either of the other two sites. Since damage from hurricane, fire, or wind throw would presumably result in growth increases for the surviving trees, without a sharp growth decrease, none of those influences are suspected as causes; the pattern looks similar to other known events of insect damage or disease.

Still other events appear to be coincident with climate in producing growth changes. According to climatic records, 1917 underwent a cool spring, perhaps stimulating the low maximum density for that year as well as contributing to the susceptibility of the mostly mature individuals to an insect attack. The recent decline in width and density at all three sites correlates well with decreases in spring temperatures (Conkey 1982), but the decrease may be enhanced by a changing chemical environment in the forests that has been suggested to affect tree growth elsewhere (Siccama 1982).

Finally, suspected non-climatic events may mask the expected response of growth to known climatic events. The "year without a summer", 1816 (Baron 1980), is apparently such a case: all three width series show a great increase in growth during that time, perhaps due to an increase in light and nutrient availability from the death of old diseased individuals prior to 1810. Density values had already returned to more nearly normal levels by 1816, and thus show the decrease in density that one would expect from the well-known cool growing season (Conkey 1982), but the widths may have been more strongly affected by the growth surge than by the cooler than normal temperatures

CONCLUSION

Statistical and visual examination of dendrochronological series of ring widths at peak densities reveals spatial similarities over distances of up to 200 km, indicating regional environmental control on growth that is probably climate, or climate-related. It is also clear that a one-to-one correspondence between climate and the growth pattern does not exist, even for the highly spatially coherent maximum densities. Instead, the patterns of changing ring widths and densities through the past 300 years and across the mountains of Maine show that the effects of growth are many and varying; there is a mosaic on each stand produced by age differences, canopy clearing due to wind throw, fire, and insect attacks, and regional climatic influences on the physiology of individual trees. This provides the great wealth of information on changing forest productivity which is thus represented by the spatial and temporal patterns of accurately dated ring-width and wood density series.

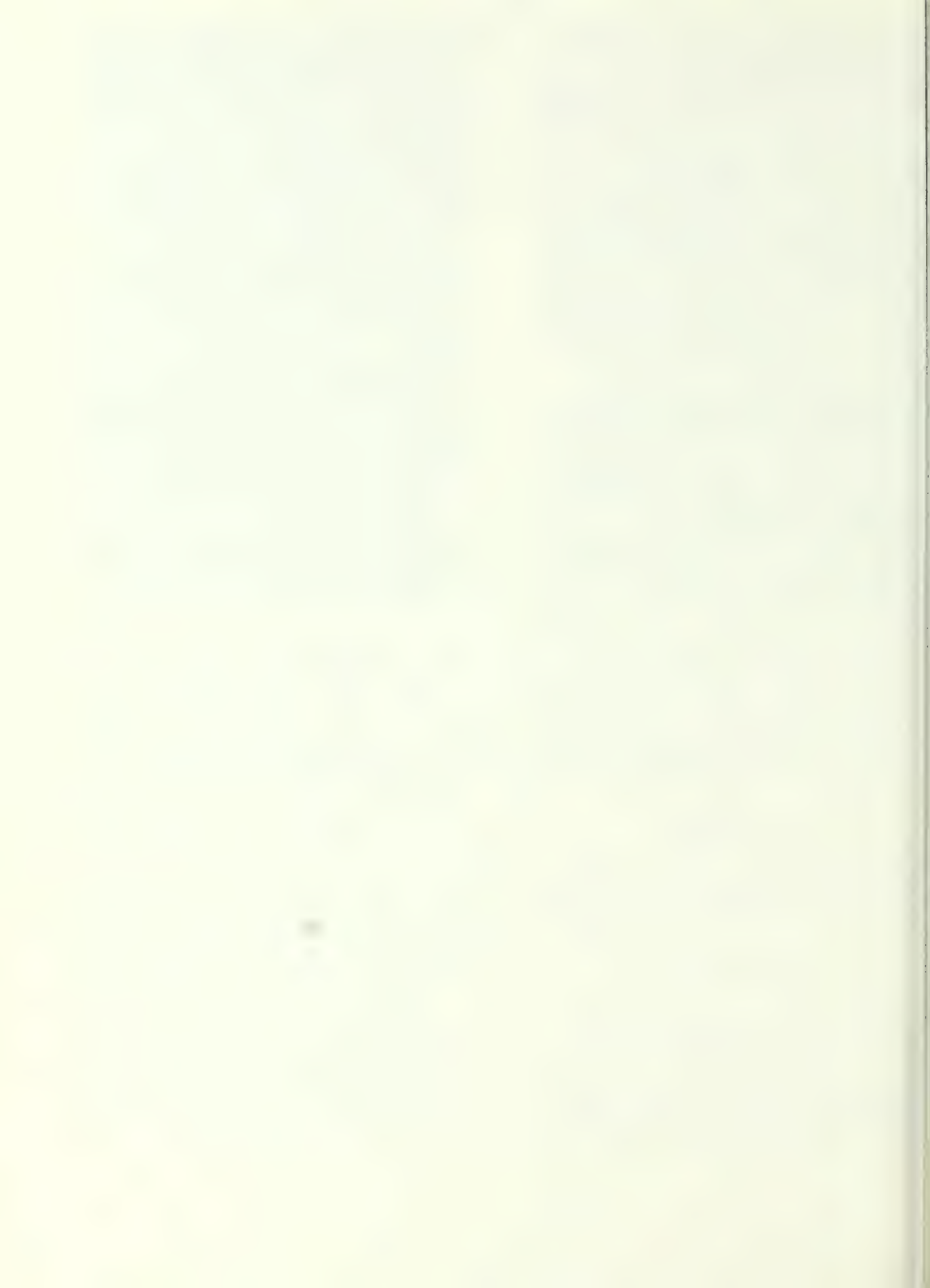
ACKNOWLEDGEMENTS

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MULTIPURPOSE SLASH PINE - GENETICS AND PHYSIOLOGY
OF GUM NAVAL STORES PRODUCTION

by

SUSAN V. KOSSUTH

Abstract.--Genetic studies show that oleoresin or gum yield obtained by the bark chipping method is under strong genetic control in slash pine (*Pinus elliottii* Engelm). Selection and breeding for increased gum yields have made significant gains in both gum production and rapid growth because the two traits are positively correlated. Thus, a multipurpose strain of slash pine, good for high gum yields, pulpwood, poles sawtimber etc. is currently in an advanced generation breeding program.

Anatomical studies of resin canals in slash pine dating to 1922 showed that the vertical and radial resin canal systems are interconnected and that gum exuded from chipped faces originates from both systems. Early work also demonstrated that the number of traumatic resin canals begins to increase about 4 weeks after chipping commences.

The fourth generation of chemicals for increasing gum yield have just begun being tested. The first were non-growth regulating chemicals, including sulfuric acid which is widely used to stimulate gum flow. The second generation was herbicides, including 2-4-dichlorophenoxyacetic acid, which was as effective as sulfuric acid. However, it was not adopted commercially because at effective levels it was toxic to longleaf pine which is also chipped commercially and grows in mixed stands with slash pine.

Ethylene releasing compounds were the third generation of chemicals. Two-chloroethylphosphonic acid (CEPA) increased gum yields from slash pine by 37 percent when added to sulfuric acid, and the effect was additive. The best CEPA treatment without sulfuric acid gave gum yields 22 percent below the sulfuric acid commercial control. Hence, sulfuric acid is considered the critical component in increasing gum yields. The mode of action of the sulfuric acid is probably to prevent crystallization of resin acids and prevent tylosoid formation while the action of CEPA is probably to release ethylene, which induces gum synthesis and new resin canal differentiation.

The fourth generation of chemicals for increasing gum yields stimulates the plant to produce ethylene. Some of these include calcium plus cytokinins and auxin plus cytokinins. They are still being tested.

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INTRODUCTION

The techniques for collection of oleo-resin or gum from living pine trees were brought to this country in 1606 when the naval stores industry was established in the South-eastern United States (Curry, 1943). Today, slash pine (*Pinus elliotii* Engelm.) and long-leaf pine (*Pinus palustris* Mill.) are the only two species used for the production of gum naval stores, which are so-named because the gum was initially used for caulking ships. Oleoresin is composed of about 20 to 25 percent terpenes and 75 to 80 percent resin acids or rosin. Today gum is used for a variety of specialty products including paint thinners, varnishes, shoe and metal polishes, perfumes, flavorings, cleaners, disinfectants, tackifiers, plasticizers, adhesives, and recently as ethylene stock for plastics.

Clements (1974) described modern techniques for collecting gum from living trees. For 1/3 of the tree's circumference at breast height (1.37m above ground), rough outer bark is removed to prepare a smooth surface from near the ground to about breast height. This process is called rossing. A collection cup is then mounted close to the ground, and just above it, a gutter or apron that spans the rossed surface and is tightly nailed to the tree for channeling gum into the cup. In early spring, a 1 to 2 cm strip of bark, chipped down to the cambium, is removed across the smoothed surface just above the gutter. This is the first streak. Either a 50 percent liquid sulfuric acid solution is sprayed on the new wound or a 50 percent sulfuric acid paste is applied as a bead across the top of the wound adjacent to the intact bark. Every 2 weeks, if the liquid is used and every 4 weeks if the paste is used, a new streak is made by chipping off another 1 to 2 cm of bark down to cambium above the last wound and the new fresh cut surface is retreated. Chippers attempt to remove just enough bark to expose some xylem tissue that has not been killed by the upward penetration of the sulfuric acid.

In 1941, research was initiated to identify individual trees that yielded significantly more gum than the average (Mitchell, 1942; Dorman, 1945) so that these high-gum yielding selections could be used in a breeding program, propagated, and the progeny used in commercial plantations. Simultaneously, the anatomy and physiology of gum yield were being studied. After the first 12 trees were selected in 1941, rapid growth, good form, disease resistance, high specific gravity, etc. were added as selection criteria

(Squillace and Dorman, 1961). Progeny of the resulting trees could then be used for several purposes, including gum yield, pulpwood, poles, sawlogs, etc., and the concept of a multipurpose strain became a reality after several years of work (Gansel, 1972). Slash pine is planted more often than longleaf pine and the program has emphasized this species.

The objectives of this paper are to summarize the past and current research on the genetics and physiology of gum yield in slash pine.

VARIATION & HERITABILITY OF GUM YIELD

Slash pines vary widely in gum yield and growth rate within and among stands throughout the natural range. No reports to date have shown that trees in a given part of the range of slash pine may be genetically superior for gum yield (Barrett and Bengston, 1964). However, early work has demonstrated that gum yield is a highly heritable character, and this finding has been verified (Squillace, 1962). Up to 3-fold differences in gum yield were documented as early as 1932 (Wyman, 1932), and within a stand of 363 20-year-old trees the best 5 and 10 percent of the trees had twice and 1.8 times as much gum as average trees (Squillace, 1965).

Using the micro-chipping technique of Ostrum and True (1946), Squillace (1962) analyzed wind and control pollinated progenies. Approximately 50 percent of the high-gum-yielding parent trees had high-gum-yielding progeny. Progeny of all the high-gum-yielding parents averaged 55 percent more gum than progeny from average yielding trees. Heritability for gum yield was 55 percent, indicating that 55 percent of the variation in gum yield among trees was due to genetic and not environmental effects. Other estimates of narrow-sense heritability for gum yield ranged from 45-90 percent, and broad sense estimates ranged from 67-90 percent (Mergen et. al. 1955; Squillace & Dorman, 1961; Goddard and Peters, 1965).

Today, less than 1 percent of the available slash pine are worked for naval stores. However, several clonal seed orchards of high-gum-yielding selections have been established because high gum yield is positively correlated with height growth (Squillace, 1965). This correlation means that high-gum-yielding trees tend to grow rapidly but not all fast growing trees are necessarily high gum yielders. Based on this information, the USDA Forest Service has continued an advanced generation breeding program for multipurpose slash pine to improve high-gum-yielding slash pine selections which have shown other desirable characteristics. Progeny of the current strain will produce 50-100 percent more gum, grow 12 percent faster, and give 12 percent more tall oil at the pulpmill than average slash pines. High-gum-yielding trees in

short-term progeny test were 24 percent higher than commercial check trees (Gansel, 1962). No correlation has been found between straightness or branch angle and gum yield (Gansel, 1965).

Physical factors that influence gum flow include the number and size of radial/vertical resin canals, flow rate, viscosity and exudation pressure of gum (Schopmeyer *et al.* 1954; Mergen *et al.* 1955; Bourdeau and Schopmeyer, 1957). Barrett and Bengston (1964) found that viscosity of gum could account for 12 percent of the variation in yield, but they did not find a positive relation between gum exudation pressure and yield as did Bourdeau and Schopmeyer (1957). The latter demonstrated that yield was inversely correlated with viscosity. Mergen *et al.* (1955) found that gum viscosity of progeny was about intermediate between those of their parents and therefore was under genetic control. Similarly, gum exudation pressure of progeny was correlated with that of the parents and also was considered a heritable character; however, gum exudation pressure and gum viscosity do not follow the same inheritance pattern (Bourdeau and Schopmeyer, 1957). Thus, four characteristics of slash pines appear to be invaluable in a genetics program: (1) obtain progeny that have high gum yields and rapid height growth, (2) low gum viscosity, (3) large numbers of vertical and horizontal resin canals, initially or in response to wounding or chemical treatment, and (4) high gum exudation pressure. The last characteristic may help protect the tree from fungal spore infection and insect pests.

PREDICTING GUM YIELD

Squillace and Dorman (1961) microchipped control and control-pollinated progeny from parents of high and average gum-yielding slash pines. Wind-pollinated progeny from high-gum-yielding parents had less gum than control-pollinated progeny from high-gum-yielding trees from the same parents. However, a highly significant correlation coefficient of 0.89 was found between control and wind-pollinated progenies of the same parents. This means one can predict the yield of progeny from a controlled cross if the progeny from the wind-pollinated parents have been evaluated.

Naval Stores producers may chip a given tree for 10 to 12 years. If it is a low-yielding tree, the time and labor expended may be uneconomical for the yield obtained. A correlation coefficient of 0.76 was found between yield of the first 4 streaks of chips and total yield over a 4 year period.

Thus, early-season yields can be used to predict long-term production (Squillace *et al.* 1969).

Microchipping is also a valid means for evaluating individual trees, such as in a progeny test (Kraus, 1965). This technique estimates the oleoresin content of a tree using a sample as small as a few ml taken from the xylem of a tree. Gum yield from two microchips taken from each of 75 slash pines in May, July and September were closely correlated ($r=0.758$) with yields obtained by standard chipping procedures in the same season on the opposite side of the same trees. However, the coefficient of determination was not high enough to select individual trees by the microchipping procedure. Coefficients were developed for predicting gum yield from full-face chipping of trees in various diameter classes. The microchipping procedure has been adapted for use on 2.5 to 3-year-old progeny in closely spaced plantings (Squillace and Franklin, 1968). Progeny testing requires a great deal of time in an advanced generation breeding program and procedures for early detection of genetic traits are needed. Because gum yield is positively correlated with height growth (Squillace, 1965) and microchipping yields are related to full-face yields (Kraus, 1965), the microchipping technique has been adopted for progeny testing (Squillace and Franklin, 1968). No tests have been conducted to show that high microchip yields on a given tree at age 3 also result in high yields 15 to 20 years later when the same tree is full-face chipped for several years. We are in the process of obtaining this documentation.

The potential exists for reducing the progeny testing time to 2 months by evaluating the extractives and/or terpene content in progeny test seedlings (Kossuth, unpublished). The basis for this concept is twofold. First, Franklin *et al.* (1970) found a positive correlation ($r=.5$) between gum yield and extractives content in slash pine. Second, Funes *et al.* (1973), using 2-month-old *Pinus pinaster* seedlings from average and high-gum-yielding parents, found that progeny of the high-gum-yielders had 4 times the terpene content of progeny from average-gum-yielders. The system would need to be tested from seedling to microchipping to full-face chipping to verify its applicability and degree of usefulness.

THE RESIN DUCT SYSTEM

Normal resin canals are found in the genera *Pinus*, *Larix*, *Pseudotsuga* and *Picea* (Panshin and DeZeeuw, 1964). Traumatic resin canals arise as a result of stress or injury. Normal and traumatic resin canal differentiation is a post-cambial phenomenon. They arise schizogenously in vertical (longitudinal) and horizontal (radial) rays. The middle lamella disappears, gum is

secreted into this region, and the "canal" is created. The vertical and horizontal systems anastomose (Gerry, 1922). The surrounding thin-walled parenchyma cells divide along their long long axis and differentiate, forming the secretory epithelial cells. Epithelial cells of normal resin canals in *Pinus* are thin walled (Kibblewhite and Thompson, 1973) but those of traumatic origin are thick walled. In slash pine, resin canals have three layers: the inner epithelial cells, a surrounding layer of intermediate cells, and the outer cells (Schierbeek, 1952). Resin canals are always found associated with the ray system.

On a dry weight basis, gum content of slash pine averages 4.7 in sapwood and 25 percent in heartwood. Resin soaking, or the filling of tracheids with gum, normally occurs in heartwood formation. Sixty percent of the vertical resin canals in slash pine were found in the latewood of mature trees, but only 5 percent of rays potentially available for vertical resin canal differentiation actually contained a resin canal (Hobert, 1932). As long as heartwood formation has not occurred, these rays would be available for traumatic resin canal formation. Up to age 8-10 years, resin canals are commonly found in the earlywood as well as the latewood.

Vertical resin canals in slash pine are 70-120 microns wide and are usually found in the heartwood; radial resin canals are always less than 70 microns wide (Koch, 1972). Other reports indicate that widths of both horizontal and vertical resin canals are around 55 microns (Hodges et al., 1981). Slash pines contain 219 vertical resin canals per square inch in cross section, 458 horizontal resin canals in tangential section, and 20,000 uniseriate rays in tangential section (Koch, 1972).

Hobert (1932) found the number of vertical resin canals in slash pine increased with ring width from 200 to 300 canals per square inch when growth rings were 0.22 and 0.44 inches wide, respectively. The number of horizontal resin canals was not related to ring width. Mergen and Echols (1955) studying 30-year-old slash pine wood samples found: (1) the number of radial resin canals per unit area was highest near the pith (about $86/3.03\text{cm}^2$), decreased to about the twentieth ring, then remained fairly constant (about $52/3.03\text{cm}^2$). (2) the number of radial resin canals decreased with decreasing ring width from about $86/3.03\text{cm}^2$ for growth rings 0.3 inches wide to about $53-56/3.03\text{cm}^2$ for growth rings 0.1 inches wide and remained at about that level in narrow rings. Ring width declined with age

as did the number of resin canals. (3) the size of radial resin canals decreased with age from about 0.0029mm^2 in 10-year-old wood to 0.0023mm^2 in 30-year-old wood. (4) radial resin canal size also decreased with ring width from about 0.00285mm^2 at 0.3 inches ring width to 0.0023 in 0.12-inch ring width.

Within 1 to 3 months after the chipping season begins in the early spring, gum yields increase. This increase has usually been attributed to rising temperatures reducing gum viscosity and hence increased rate of gum flow (Harper and Wyman, 1936). However, several anatomical studies have shown that the number of vertical resin canals increases as much as 10-fold, especially in new wood produced above where chipping begins (Gerry, 1922; Busgen and Munch, 1929). The vertical and radial resin canal systems are interconnected (Gerry, 1922). As the bark chipping progresses into the area of new resin canals, these are also contributing to the increased gum flow (Gerry, 1922). Many naval stores workers have successfully used the advanced streak to increase early yields (Herty, 1911). This streak is similar to the common one, but it is put on several weeks before the regular season begins. The early wounding allows time for traumatic resin canal differentiation which takes 4 weeks or less (Gerry, 1922). Although slash pine specifically has not been studied, the length of vertical resin canals in other species has been found to be up to 80 cm and to increase in length with the age of the tree (Werker and Fahn; 1969). This increase may help to account for higher gum yields from older trees. Slash pine has been shown to have more resin canals than longleaf, shortleaf, or loblolly pines (Hodges et al., 1981) and in general, slash pines yield more gum than the other species.

USE OF CHEMICALS TO INCREASE GUM YIELD

Around 1930, a search was begun to find chemicals with which to treat trees to increase gum yields. From 1930 to 1950 a variety of chemicals unrelated to growth regulation were applied to bark-chipped trees in attempts to increase gum yield; among chemicals tested were organic and inorganic acids, bases, salts, solvents, oxidizing and reducing agents, alcohols, poisons, ethers, and oils (Snow, 1944; Schierbeek, 1952). In the 1940's, sulfuric acid, which worked quite well, was introduced for commercial use because it not only increases yields but also prolongs gum flow so workers do not have to chip as often. Gum probably stops flowing because of crystallization of the resin acids and/or tylosoid formation, not because the resin canals are depleted of gum. The mode of action of those chemicals that improved yields was probably to (1) prevent crystallization, (2) prevent tylosoid formation and

(3) enhance the wounding effect.

After 1950, a wide variety of herbicides were tested to improve gum yields. Schopmeyer (1948) conducted the first tests with 2,4-dichlorophenoxyacetic acid (2,4-D) using esters and salts of the parent compound. Although 2,4-D alone was demonstrated to be as effective as sulfuric acid on slash pines, it was not adopted by the industry because effective concentrations of 2 percent 2,4-D on slash pine were toxic to longleaf pine. Most stands are mixed and the effort needed to separate species in the field was too great (Clements, 1964, 1970).

The third generation of chemicals tested to improve gum yield was plant growth regulators. Research begun in 1978 centered on ethylene and ethylene-generating compounds for several reasons. The rubber industry uses a commercial formulation containing 2-chloroethylphosphonic acid (CEPA) to stimulate latex production in rubber trees. At pH levels above 3.5, CEPA degrades to release ethylene (Abeles, 1973). Latex production in rubber trees by laticifers is similar to oleoresin production in slash pine, and both products have the same early precursors in their biosynthetic pathway. Plants respond to wounding such as occurs in the chipping procedure by producing ethylene gas at the wound site (Saltveit and Dilly, 1978). Ethylene is a natural plant hormone that is readily soluble in water and could easily be translocated in slash pine. The addition of ethylene to that already generated by the trees from wounding might increase gum yields through increased synthesis of gum and by increases in the number of resin canals differentiated.

A series of factorial experiments were undertaken to test the effect of several levels of CEPA alone and in combination with several levels of sulfuric acid on gum yield in slash pine (Kossuth and McReynolds, 1982, 1983). Both liquid and paste sulfuric acid formulations were tested because producers use both. Gum yield was increased by 37 percent over the commercial 53 percent sulfuric acid paste by lowering the sulfuric acid level to 25 percent and adding 5 percent CEPA (McReynolds and Kossuth, 1983). In treatments with CEPA alone, yields increased with increasing CEPA levels but all were at least 22 percent less than that from the commercial 53 percent sulfuric acid paste. Spraying to runoff with 21.6 percent CEPA (applied as the full-strength commercial formulation of Ethrel ^{3/} over the rossed bark surface at the beginning of the year or spraying the 21.6 percent CEPA on the bark just above each

streak as it was chipped also increased gum yields close to the best sulfuric acid plus CEPA pastes. Gum yields decreased at the higher CEPA levels.

Results with liquid sulfuric acid formulations (McReynolds and Kossuth, 1984) were similar except that higher CEPA and acid concentrations were required to increase gum yields. The greatest increase over the commercial control was 20 percent in the 50 percent sulfuric acid plus 15 percent CEPA treatment. In these treatments, gum yields did not decline at the 25 and 50 percent sulfuric acid plus 15 percent CEPA levels and higher sulfuric acid and/or CEPA levels may increase gum yield even more.

There was no synergistic interaction of the sulfuric acid and CEPA. The sulfuric acid is essential and CEPA seems to only add to the increase in gum yield. The paste formulations were more effective at lower concentrations because the paste bead stays at the application site and soaks in, whereas the liquid runs down the face of the tree. Long-term studies may show that with the liquid treatments resin soaking occurs on the lower part of the face which receives repeated application because of runoff from above.

The mode of action of CEPA is probably to release ethylene which induces (1) added gum production in existing resin canals and (2) differentiation of new resin canals, perhaps above the number induced by the normal chipping procedures.

A fourth generation of chemicals for increasing gum yields has already received preliminary testing (McReynolds and Kossuth, 1983). These are chemicals which alone, or in combination, stimulate the tree to produce ethylene. High auxin concentrations induce plants to produce ethylene (Kang *et al.*, 1971). The success with 2,4-D treatments is probably attributable to this process. Calcium plus kinetin (Lau and Yang, 1974) and auxin plus kinetin (Lau and Yang, 1973) stimulate plants to produce ethylene and these treatments have increased gum yield from chipped slash pines (McReynolds and Kossuth, 1983).

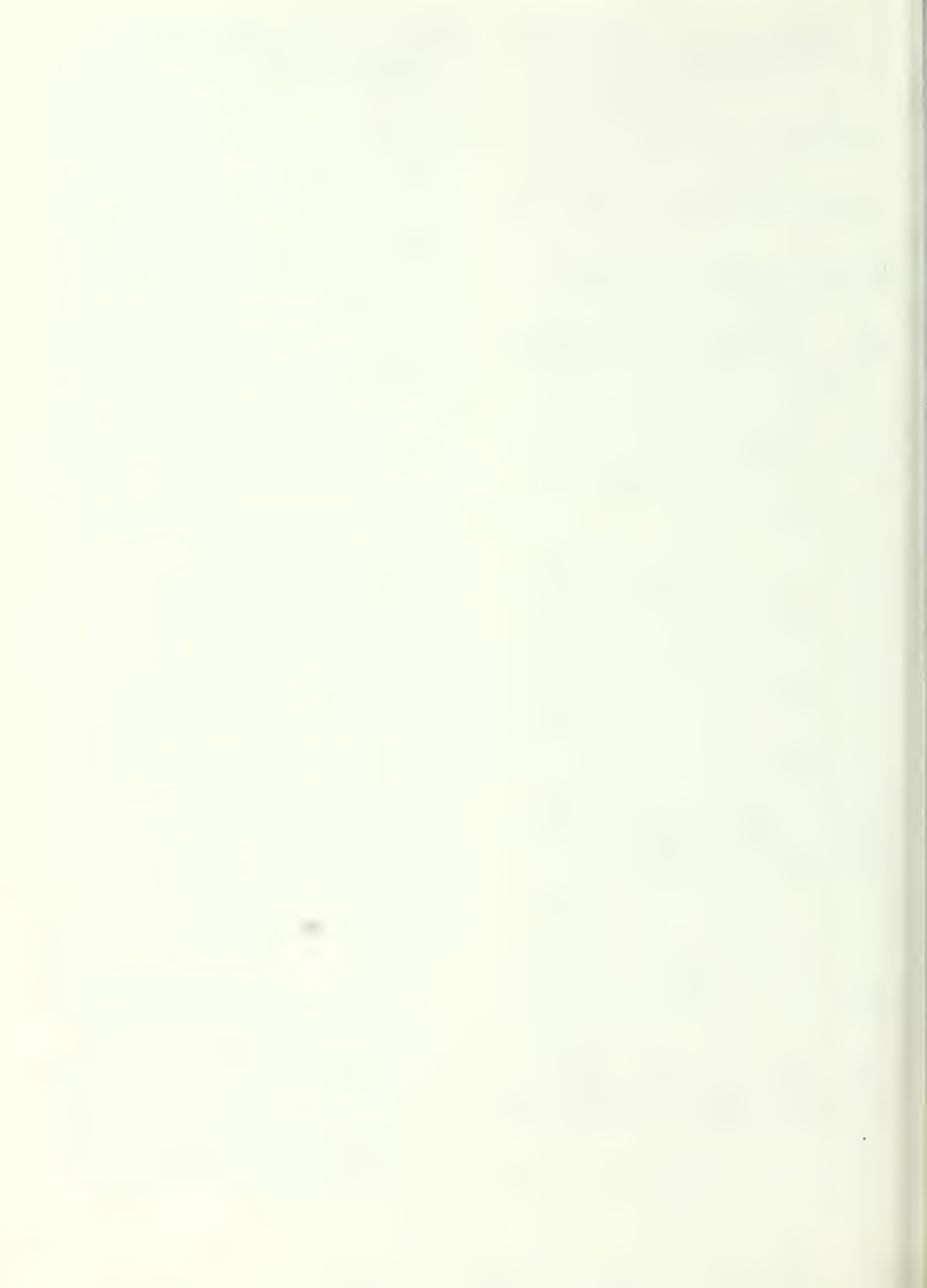
More research is needed to identify chemicals which may stimulate resin production versus those which cause the formation of traumatic resin canals. Basic research on the biosynthetic pathway for the components of oleoresin is also needed. The oleoresin resulting from CEPA treatment has been much less viscous than that from the commercial control, indicating that there is preferential synthesis of the terpene fraction of the gum.

^{3/}Mention of trade names is to identify materials and does not constitute endorsement by the USDA.

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PANEL QUESTIONS

FOURTH SESSION: Forest Productivity: Problems and Achievements

QUESTION (A.M. Carey): What do you consider to be more important for maintaining long term forest productivity on these sites, increasing the root density by more intensive initial site preparation or improving the nutrient status of the affected rooting zone. The reason I'm asking this is that I think within our career spans what we are going to be seeing is more intensive forest culture because of more intensive pressure and competition between forest uses and agricultural uses.

RESPONSE (S.J. Riha): One of the points I was trying to make for mature stands is that I think in a lot of situations root density is not limiting water uptake; on the other hand root density very well may be limiting nutrient uptake. In that situation more intensive cultural practices, such as fertilization, would be useful. In terms of site preparation for tree seedlings, the volume of soil that the roots are exploiting definitely limits water uptake. The idea for mature stands is that they have already exploited the total soil volume that is available to them and basically if they've got a few roots in wet soils they are going to make it somewhere down deep enough. But for tree seedlings, anything that would stimulate root growth and increase the rate at which those roots exploit the soil volume would be useful for decreasing water stress.

QUESTION (A.M. Carey): Has there been any work done in altering root resistance chemically; in other words, the application of another chemical to decrease root resistance.

RESPONSE (S.J. Riha): That's interesting. I haven't seen any work like that. There has been a lot of controversy in the past 10 years or so about root resistance. In the 1960's Gardner wrote an article basically talking about how slowly water moves through

dry soils; and most of you who have ever taken a soils course probably got that impression that water moves very slowly through dry soils -- so the assumption was that water uptake was limited by movement through soils. Then it was physiologists really who started trying in various ways to measure root resistance. -- It's not an easy thing to measure; and I would say there are still a lot of problems with the way root resistance is measured. They found that it was quite high and, in fact, a lot of people reported it was much higher than soil resistance. Now there is still some debate about how much contact resistance there is -- right between the soil and the root; and that is very difficult to delineate from either end. The problem right now is that no one has really concluded where that big resistance in the root is. It is basically thought to be in the endodermis with the casparian strip; but exactly how water moves from the cortex into the xylem; how much it moves apoplastically and how much it moves simplastically is not known. So in terms of chemical alterations, that would just be a hit or miss thing because it would be difficult to say exactly what kind of chemicals you should use and where you would want to affect this. The controversy right now over resistance is how much temperature affects it, how much something like dormancy might affect it, how much variability there is say between suberized and unsuberized roots, and also whether the resistance in the root itself is flux-dependent. There has been a lot of suggestion that the quicker the water flow through the plant, the higher the resistance to flow. That may just be an artifact of the measurement system. So I would say at this point, no, there has not been any work with chemical alteration of root resistance.

QUESTION (S.L. Stout): I would like to start by saying, Kathleen, that I really enjoyed your paper and I have several questions, many of which arise from my

own very deep interest in the topics you covered. What are the more important management implications of what you are doing then, in terms of a large landowner - a landowner who say has holdings across the whole south? Could he use your model in conjunction with maps of rust hazard to choose management strategies for stands and manage for solid wood products in low risk areas, for example?

RESPONSE (K.E. Moore): Yes, that is definitely one way you can avoid impact - just adjust your expectations. I think that is a very feasible kind of thing, because the tall resin yields are higher from the galls themselves. There is quite a bit of resin in those galls; so while the pulp yield from the galls themselves goes down, it turns out economically, as shown by McVeld, that is more than offset by increased tall resin yields. If you go ahead and pulp those trees chances are you are not going to see that kind of product loss.

QUESTION (S.L. Stout): In some of your most recent work, it seemed to me as if there was some implication of yield loss associated with higher levels of aggregation incidents.

RESPONSE (K.E. Moore): I think it went the other way. The position of the line decreases .. that's why it didn't do what I expected it to do. What I would anticipate is that the intercept for the uninfected stands should be the same, but the slope should be steeper. What I found was that the slopes were the same for the two levels of aggregation. It may just be that I haven't done enough runs yet to be able to get a good line out of that.

QUESTION (S.L. Stout): You mentioned that the disease cycle is dependent upon an essential phase in an alternate host; I wondered if you could talk some about whether or not a large-scale landowner could find information about where alternate hosts are versus where pine plantations are, to either control or minimize impact of disease on pine plantations.

RESPONSE (K.E. Moore): My opinion is yes, very much so. That goes contrary to almost anyone else's opinion regarding this disease. Part of that is the history you may or may not be familiar with -- the control attempts earlier

in this century with respect to white pine blister rust. It was an eradication program to get rid of the alternate host. Everybody kind of scoffs at that now, because -- who had the picture of all the men in the trees trying to get rid of the egg masses -- it was the same kind of thing. They just sent out these huge crews of men, I understand, to get rid of the alternate host for white pine blister rust. I think that is part of why people laugh when I talk about oak control. Nonetheless, the fact of the matter is the history of fusiform rust is such that one of the major reasons that we are experiencing an epidemic of this disease now is that our forest management practices have brought the alternate host in closer contact with the pine host. The fact of the matter is you have got to have the alternate host -- it has got to be there in order for new infections to occur. What we need to know more about is the dispersal process and find out in a very sophisticated way what conditions affect dispersion and which plantations may respond to management of the alternate host.

QUESTION (J.R. Flack): Laura, first of all I would like to thank you very much for the paper that you gave, I thought it was excellent -- it was very well presented and gave the kind of detail that I really like to see. When I knew that I was going to have to make some comments to Laura at this meeting I did a quick search of the literature to find out who has been working in this area recently and it dawned on me very quickly that Laura isn't just one of the few, but she is certainly in the forefront of this work that is going on in the northeast. So I feel very privileged to have been able to meet with her and look at her work. I would like Laura to explain how it is that she can do such refined work now, whereas in the past it was much more difficult. Where she can use not only tree ring width but also the cellwood density to come up with fairly precise data, so that she can arrive at an apparently accurate set of data from only 30 cores out of 15 trees. Please explain to us the density in the tree ring width differences.

RESPONSE (L.E. Conkey): The whole technique of taking wood density was developed in areas other than the arid southwest where correlation between tree ring width and climatic factors is so prevalent and so easily done. The first people working in wood density from a forestry point of view were in France. The technique has spread to places in Switzerland. There are many instances of use of this technique in different applications, but in dendrological applications it is very limited in where this is taking place. Part of that is due to the greatly increased cost, both in time and in finance, of getting density information. The technique involves taking cores from trees, but then subjecting them to x-rays, deriving an x-ray film that one can develop and analyze for relative opacity of the rings from one part of the growing season to the next. That is what produces those density traces that I showed you on that one slide. That is done merely by figuring out how the density of the x-ray film, which is cellulose acetate, how that relates directly back to the wood density itself. There is a lot more equipment needed, a lot of expense and a lot more time involved in getting that information -- and in a lot of places it hasn't seemed to greatly increase the amount of information obtained over what can be obtained much more easily by just looking at ring widths themselves, which you can do by just looking and counting and measuring, cross-dating. For instance, in the Colorado plateau there has been some work done with wood density versus ring width that shows that the ring widths have more information from a climatic point of view than do the densities themselves. But in an area such as this where the ring width correlation to the climate is so low, density definitely appears worth the added investment.

QUESTION (J.R. Flack): Thanks. One other question that I have has to do with your historical analysis -- and we talked about this a little bit at the break. But maybe you could further elucidate why it is that you think changes are insect related when you look at your 19th century record as opposed to merely a temperature differentiation in your data.

RESPONSE (L.E. Conkey): When I did climatic analyses I used two major sources of information, one involved just the

weather bureau records that we have for the last hundred years; that is readily available -- temperature, precipitation, drought severity, disease, water stress and other such factors. That will take us back to the very latest 1800's in Maine -- Most climatic stations only go back to 1895 maximum. But there are some researchers at the University of Maine who have been culling records from historical sources -- diaries, records that people kept a long, long time ago whether in association with their own farms and crops or just for a very esoteric academic kind of interest. At almost every university there was somebody taking records of temperature and precipitation as soon as some of these places got going. These researchers at the University of Maine have put together a very impressive record of historical climate based on such records -- qualitative and quantitative. The quantitative records are easy, the qualitative records they subject to content analysis to get some kind of quantitative information from the qualitative records. I was able to use those records in comparison with my own climatic reconstructions that I derived from the density and the width, and came up with some very good correlations in some instances. That is on a more specific level. On a more general level, I mentioned the 1816 year without a summer; there was another cold spring in 1812. Things of that nature that are more generally known and talked about, different kinds of things that happened in the past in terms of climate. But there are two significant sources of deriving climatic correlations with the tree ring data. As far as insect infestation, disease, wind throw, things like that -- at this point it is entirely qualitative. On my point I found very little historical information on that, and as I was talking with one of you just a little while ago, when people say there have been budworm infestations in the northeast over the last 300 years, well they are getting that information from the same kind of data that I have. That is, the tree ring records themselves, so it gets rather circular rather quickly -- and I can't really rely on that kind of information.

QUESTION (M.Morselli): Susan, the other Susan, I am very happy to have to comment on your paper because for

once I will not speak of maple sap flow but resin flow. The first question -- you are talking about genetic differences, naturally; you said that the maximum yield in a progeny test is after about two months; but what is the optimum age for resin yield in a natural stand? Did you way 10 years at some point?

RESPONSE (S.V. Kossuth): The industry people have established a rule of thumb that they don't work trees that are smaller than 9 inches. The reasoning is that on the smaller trees the 1/3 circumference area is less and therefore they will be getting less yield from it, and that it takes a certain amount of time just to get to each tree and to make each treatment and collect. So, in the end they don't get enough gum from working smaller trees. So they usually work larger ones. One of the problems that one has in reading the literature is that initially, especially with the breeding program, they would take say high gum yielding trees and plant them with commercial checks, and after 10 years or whatever go in there and chip and say -- ah ha, the high gum yielding trees are high gum yielding -- look at all this gum we have. Well, they were also fast growing, so they were also larger in diameter -- and no corrections were made for the diameter size; so, yes, larger trees yield more gum, but that is because you are chipping a larger surface area to get that gum. So all of the data I presented was corrected for -- I forget what the units were, I think I had barrels per crop, that's 435 pounds in a barrel per 10,000 trees in a crop -- but those numbers came from grams per inch dbh. The face width was whatever the dbh was on the tree. So you can get good yields from smaller trees, it is just that it is not economical to go back that often for small amounts at a time -- you need larger amounts.

QUESTION (M. Morselli): How long does the season last?

RESPONSE (S.V. Kossuth): In Florida they start in March and go right through October. That is based on the assumption that it needs to be warm. I guess I forgot to follow that up the advanced streak I promised. The empirical observations were that the increasing gum yield came sooner if you put on that advanced streak; and they would put it on in the

cooler months, like January-February, and start chipping in March and April and get much larger yields at that time because of the advanced streak, which I believe was simply the wounding effect, production of ethylene, and it takes about a month for resin canals to differentiate -- so after 6 weeks or more, after an advanced streak, they'd start chipping and they would have more resin canals all ready to be contributing gum.

QUESTION (M. Morselli): The other question was on elaborating a little more on the ethylene production, in terms of the exudation pressure. I would like to know a little more about the mechanism. Is the exudation pressure correlated with the higher ethylene production in a normal situation?

RESPONSE (S.V. Kossuth): The exudation pressure is a heritable character, so there will be a correlation of what kind of pressure you get in progeny with the parents form which they came. What I don't know is if there is a relationship between ethylene production and that pressure. The physical factors involved in gum flow that have been considered are the size and number of resin canals, the flow rate, the viscosity and pressure have been shown to be under genetic control, but their affect was not of a high enough magnitude on total yield that they were used as selection criteria in the breeding program.

QUESTION (M. Morselli): Has anybody studied the pressure -- where it comes from really?

RESPONSE (S.V. Kossuth): Yes, it has been studied and it shows a diurnal fluctuation in that the pressure is very high early in the morning and it drops off during the day, on towards the night, then builds up again at night. It follows the same pattern as the water stress situation would during the day. What is probably happening is that the pits in the tracheids which are conducting the water, are in contact with those parenchyma cells, and that as less water is taken up or high transportation rates occur, there is a decrease in the amount of water available to those epithelial cells around a resin canal -- so they become a little bit flaccid and that reduces the pressure. Then it builds back up again in the night.

QUESTION (M. Morselli): That is exactly what I wanted to hear, because you didn't mention it. The other thing is if there was any correlation with temperature in any way?

RESPONSE (S.V. Kossuth): Very much so. What they had done was they would go out with ice packs and put them on a tree, then they would chip; when they would cool the tree it would increase the viscosity and decrease the flow rate; and I doubt that it was having an effect particularly on the pressure. In the same way, they would wrap them up in blankets and so on early in the spring and try to insulate them against cold nights; then they could get better flow early in the day. But there is a very definite seasonal pattern in how much flow of gum there is in that very first day after chipping; it at least quadruples the amount that you get in the first day from, say early March to July, is when it would peak. So some of that is bound to be temperature and some of that, I believe, is also the number of resin canals.

QUESTION (M. Morselli): Speaking of this, does tree exposure make any difference?

RESPONSE (S.V. Kossuth): It should, but doesn't. You would think if chipped on one side or the other -- the data never showed that there was a difference, but you would think there would be, but they haven't been able to show that.

QUESTION (M. Morselli): The other question I think is the last, because I'd like to let the other scientists here ask questions. What is the damage to the tree, not only by the act itself of cutting so much of it around the bark, but also the damage of the acid -- and certainly you are saying from your studies that acid needs to be used on 53% -- I don't know what really in the long range is effect to the tree in terms of opening this to bacterial invasion, insect invasion, fungi invasion, mortality of the trees?

RESPONSE (S.V. Kossuth): The main problem has not had to do with wood quality because that outer part of the tree in making any form of lumber is usually cut off as the outer slab; so the wood quality doesn't suffer. We do have to be very careful about insect attacks; and I was telling Barbara about lindane because the industry regularly will spray the lower part of the tree,

the bottom 3 or 4 feet, with lindane to prevent initially bark beetles, but also ambrosia beetle attacks, because that oil resin has a lot of the volatile terpenes in it which are very good insect attractants. If all goes well, that is not a problem to a naval stores operation; if we have a very dry year it creates a water stress in the tree. We already have created a tremendous stress by chipping the tree, and those combinations are devastating. The reason that I know that is because we did a pilot type test with a producer and it was on a flat wood site and it was very wet and shortly thereafter the industry came in and ditched the area. So it lowered the water table because they were now draining off the water, and it changed the water relations -- tremendously stressed the trees. Normally a producer would have just stopped everything when they came in and ditched, recognizing that that was going to create a water stress and in combination the operation would be no good. So we have some data that does say precautions need to be taken, we are increasing the stress on the trees, and that when these combinations start adding up they can be lethal. All of the trees that are worked are not owned by the people working them. They are leased -- so if you are the timber company and you are leasing trees and somebody comes in and kills 30% -- it's a very bad situation.

FROM THE AUDIENCE

QUESTION: For Laura, also, Given your knowledge of state-of-the-art dendrochronology, do you believe it is possible to isolate our climatic factors such that one can attribute growth loss or a decreased wood density to acid precipitation?

RESPONSE: What a tricky question. It is very much a concern right now in dendrochronology to try and isolate that climatic factor, and has been done with varying degrees of success in different areas. In a very closely controlled study, I think one can differentiate the effects of climate from other environmental factors. It gets exceedingly difficult in areas of, for instance, the eastern US where the climate, as I've shown I think, the varying influences on growth are very, very difficult to differentiate one to

another. There are some techniques of deriving what might be the climatic response of growth, but this too is being revised at the moment -- there is a dissertation underway at the University of Arizona where these response functions are being very intensely studied to see if that indeed is a good way of deriving what the climatic influence might be. But that is a hot topic.

QUESTION: Laura, I was wondering if you could comment on whether there are techniques that you use in dendro-chronology that could be used in studies like fertilizer response, or response of a stand to insect attack -- to actually determine if there is an effect -- in a more sophisticated way than just looking from a volume of growth response over a long period of time.

RESPONSE: I think a lot of the studies that have been done on fertilizer effects have included what kind of differences there are in growth, certainly by looking at diameter growth. Now whether that, what is usually a short-term, study can be extrapolated for a whole stand for instance over a long period of monitoring might be of great use. Certainly, in that regard, once you start working with long time periods dendrochronology becomes very useful. On the short term you have much greater control over what is happening in what year in terms of growth, and so dendrochronology per se is less useful, but certainly there is potential for its use in long term studies of insect infestation or fertilizer studies, I would think.

QUESTION: If you look at the data base of what people work on now, like what is known about how trees respond to insect attack and fertilizing application, where do you see the biggest gaps in information that would be useful to you? Is there good data on those types of responses?

RESPONSE: There isn't always, and maybe I'm just unaware of it. I've looked at -- for instance, the University of Maine Extension Service has put out a number of publications on the effects of fertilizer in this or that individual situation. The difficulty from my point of view is that there is very little generalization made -- and maybe it is just not possible -- but I would like to be able to say in looking at the record in the past I

can see this or that piece of evidence that seems to fit is with what has been seen on the shorter time period -- and that has been hard to do. It is very hard to generalize, I think.

QUESTION: Susan, what effect do soluble heavy metals have on water uptake?

RESPONSE: Well that is an interesting question. I think it would depend which heavy metal you are talking about. Something like aluminum, which I know you may be interested in, there is so many possible modes of action of aluminum toxicity in the roots -- there are so many that have been proposed in the literature, it would be difficult maybe to say. But one of the things some of the people at Cornell are hot on, they feel like aluminum might -- they have done some work, I believe it is with corn, aluminum tolerant and intolerant species -- they think that aluminum is complexing in the cell wall and that in turn would decrease the elastic modules of the cell wall, and therefore there would be problems with growth and expansion of the cell carrying the cell wall. This would break up the integrity of the root. Now, my guess is that given that whole scheme of things in terms of water transport through roots, through the endodermis and into the xylem, that just breaking up the cell wall would probably have more effect on disease infestation. Probably some of the pathologists would be better able to comment on that than myself, than on water flow itself. I think you would have to actually change either the symplastic or apoplastic movement of water and I'm not sure at this point how heavy metals alone would affect that. Maybe some of the other physiologists have some comments on that.

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FIRST SESSION:

Biological Aspects of Forest Pest Control

Moderator:

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"Predicting response of forest defoliators
to insecticides"

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Jacqueline L. Robertson, Project Leader,
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"Differential population characteristics
of western spruce budworm"

Jacqueline L. Robertson and Molly W. Stock

"Nucleopolyhedrosis virus transmission
in the gypsy moth, Lymantria dispar
(Lep.: Lymantriidae)"

Kathleen S. Shields, Research Entomologist,
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"The short- and long-term effects of
insect attacks on trees"

Barbara C. Weber, Project Leader, U.S.
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SECOND SESSION:

Perceptions of the Forest and Its Uses

Moderator:

Betty Wong, Plant Physiologist, U.S. Forest
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"Displacement: One consequence of not
meeting people's needs"

Dorothy H. Anderson, Research Social
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"The handicapped user in outdoor recreation resource environments: Implications for resource planners"

Lou G. Powell, Assistant Professor,
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THIRD SESSION:

Wildlife within Forest Ecosystems

Moderator:

Betty Wong, Plant Physiologist, U.S. Forest Service, Northeastern Forest Experiment Station, Burlington, Vermont

"Amphibian and reptile habitat association in selected forest types in the Northeast"

Deborah Rudis, Associate Wildlife Biologist, U.S. Forest Service, Northeastern Forest Experiment Station, Amherst, Massachusetts

"Deer densities and forest regeneration"

Nancy G. Tilghman, Research Wildlife Biologist, U.S. Forest Service, Northeastern Forest Experiment Station, Warren, Pennsylvania

"Patterns of wolf predation and effects on moose feeding habitats"

Joan Edwards, Assistant Professor, Department of Biology, Williams College, Williamstown, Massachusetts

FOURTH SESSION:

Forest Productivity: Problems and Achievements

Moderator:

Margaret M. Harris, Research Soil Scientist, U.S. Forest Service, Northeastern Forest Experiment Station, Burlington, Vermont

"Water transport in soil and roots: Influence of root properties on water uptake"

Susan J. Riha, Assistant Professor of Forest Soils, Cornell University, Ithaca, New York

Mary Ann Levan, Graduate Research Assistant, Department of Agronomy, Cornell University, Ithaca, New York

"Impact of fusiform rust on loblolly pine plantations"

Kathleen E. Moore, Research Forest Pathologist, International Paper Company, Tuxedo Park, New York

"Dendrochronology and forest productivity: red spruce wood density and ring width in Maine"

Laura E. Conkey, Assistant Professor, Department of Geography, Dartmouth College, Hanover, New Hampshire

"Multipurpose slash pine: Genetics and physiology of gum naval stores production"

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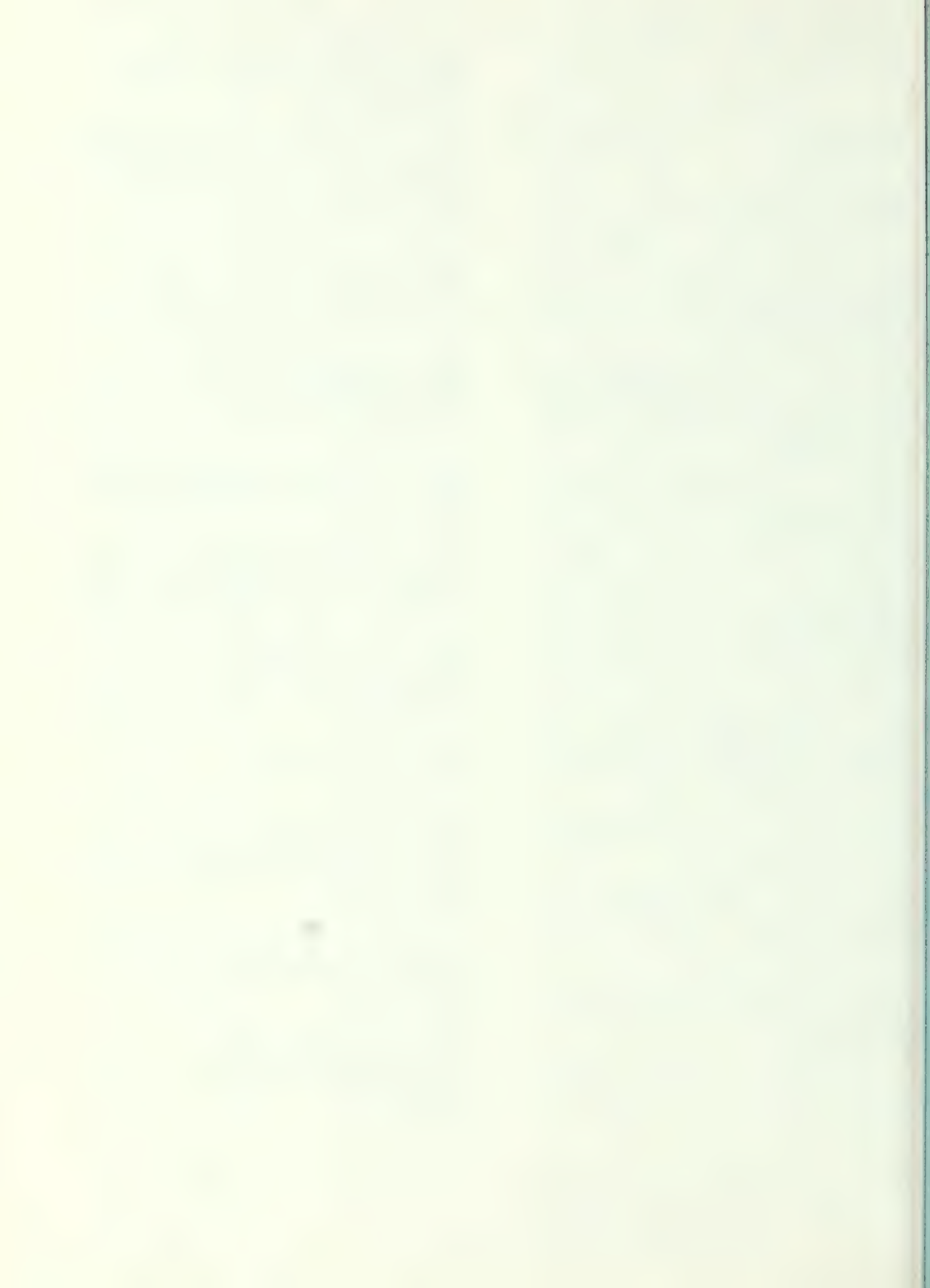
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Green Woods Model: A Forecasting Tool for Planning Timber Harvesting and Protection of Spruce-Fir Forests Attacked by the Spruce Budworm

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Abstract

A dynamic model of budworm-infested spruce-fir forests is described. The Green Woods Model allows managers and analysts to predict forest composition and structure that result from various harvesting and protection strategies. The forest structure is represented as a distribution of area and volume by age class, species, and forest type. This structure changes through time as the natural process of forest development (growth, budworm-caused growth loss and tree mortality, and regeneration) interact with management strategies (timber harvesting and protection). The model is inherently flexible; the rate and timing of virtually all modeled processes, both natural and management-related, are controlled by the user. Included is an example of how the model can be applied with conventional forest-inventory data. The main simulation program is coded in PL-1; auxiliary software in WATFIV is available to assist users in constructing input data and summarizing results.

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Introduction

When the current spruce budworm (*Choristoneura fumiferana* L.) outbreak became severe during the mid-1970's, managers and policymakers were faced with a difficult decision: How much of Maine's spruce-fir resource should be protected against tree mortality to sustain the present industry? Initially, a conservative stance was taken, and all infested areas were sprayed where the hazard warranted. However, the situation developed rapidly and by the late 1970's the need for change in Maine's budworm suppression policy was evident. Powerful forces, including environmentalists opposed to large-scale insecticide applications and landowners dissatisfied with the inequitable distribution of budworm spray costs, were at work to limit the size of Maine's protection program. Legislation was passed that changed dramatically the way in which Maine's spray program is funded. The switch from the "fire-control insurance policy" model to the "pay-as-you-spray" approach (Pimpf et al. 1982) forced landowners to limit protection to only those stands where spraying clearly was justified.

At the same time, the Green Woods Project was formed at the University of Maine's School of Forestry. Resources through funding provided by the Canada-United States Spruce Budworms Program (CUNUSA). Green Woods was a joint effort between spruce-fir forest managers and scientists to develop and apply an integrated protection-management system that would

reduce protection costs and maintain spruce-fir wood supplies. Major cooperators in this project were Great Northern Paper Co., Seven Islands Land Co., and the Baxter Park Authority. Collectively, these cooperators manage more than 3 million acres in Maine. The operational aspects of the program centered around harvesting and spraying treatments that were "targeted" on the basis of the balsam fir component of stands (Dimond et al. 1984).

Field application of the program on three demonstration areas was relatively straightforward. However, soon after the project's inception it was evident that a major component of the system was missing. There was no analytical capability for forecasting the long-term outcome of targeted treatments. As a result, it was not possible to predict whether certain intuitively reasonable harvesting or protection strategies would reach their stated goals.

To address this need, the Green Woods simulation model was developed. The model was designed to:

1. Capture the general structure and principal dynamics of budworm-infested red spruce (*Picea rubens*)–balsam fir (*Abies balsamea*) forests.
2. Allow forest managers to predict, through simulation, the consequences of a wide array of combined harvesting-protection strategies.

3. Stimulate additional research into particular aspects of spruce-fir forest development, with the aim of improving the manager's predictive capability.

Since its creation in early 1980, the model has been used widely in Maine. After its initial application¹, several major landowners followed with analyses of their ownerships, which encompass more than two-thirds of Maine's spruce-fir resource. More recently, the model was used to analyze the supply and demand of spruce-fir for the State of Maine (Sewall Co. 1983).

In the course of these applications, the model has undergone substantial revision. Its technical structure has been modified on the basis of recent analytical developments, and auxiliary software has been added to make it much easier to use by those who have had little or no experience with computers. The intent of this paper is to describe the model and to facilitate its distribution to and application by a much wider audience. The first section describes the model structure and illustrates how it works; the second shows how it can be applied to a typical management problem. Specific functions, sample worksheets for summarizing input data, and programming considerations are included in the Appendix.

¹ Seymour, R. S.; Mott, D. G.; Kleinschmidt, S. M. Future impacts of spruce budworm management—a dynamic simulation of the Maine forest 1980–2020. Unpublished report of the Green Woods Project; 1980. 88 p. On file at the University of Maine, College of Forest Resources, Orono.

Model Description

General Organization

The Green Woods Model is a general predictive tool that allows a manager to forecast the development of a spruce-fir forest in response to natural processes and management inputs. The forest structure is represented as a distribution of area by forest type, age class, and species. The model grows, kills, harvests, regenerates, and protects the simulated forest, and generates annual descriptions of its condition, including inventory, growth rate, recent mortality, age structure, species composition, and many other useful attributes (Fig. 1). Because the rate and timing of all processes are set by the user, the model is inherently flexible in its ability to replicate special situations.

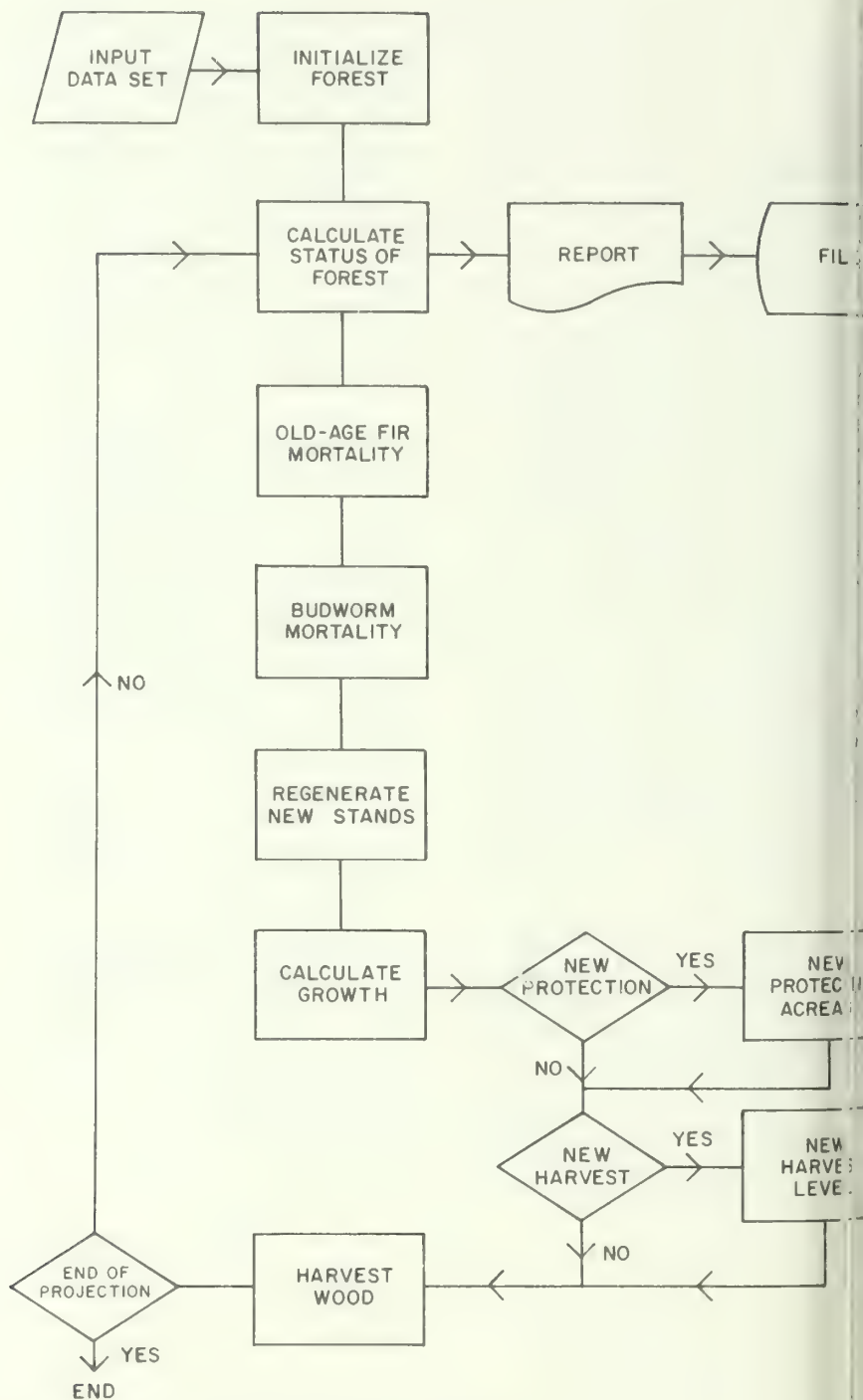


Figure 1.—Flow chart of the Green Woods Model.

Forest Structure

The Green Woods Model represents the spruce-fir forest by distributing its total area into the categories shown in Figure 2. Only the spruce-fir component of the forest is simulated. Forest types (e.g., hardwood) with little volume of budworm host species are excluded from the resource.

Attributes of this forest area—primarily species composition, stocking, and age structure—are defined by the user. During a simulation, forest structure changes as growth, mortality, regeneration, budworm attack, timber harvesting, and forest protection alter the areas and volumes in each category.

Protected and Unprotected Lands

The first major division of forest area is between lands that are either protected or unprotected against budworm attack. Protected lands are defined as the portion of

the forest with no tree mortality during a simulated outbreak. They are intended to represent the total area where a successful forest protection program (usually aerial spraying of insecticides) is applied as needed to keep trees from dying. Partitioning the simulated forest structure on this basis is a crucially important feature of the model. In addition to mortality, other modeled processes (growth reduction, regeneration, harvest allocation) also are controlled by protection status to a significant extent.

Users specify the characteristics of the protected lands and can simulate targeted programs. Through changes in protection strategies, the area under protection can be reduced or, in certain cases, increased by shifting lands between categories. This has the effect of changing the total area on which there is tree mortality and reduced growth. If no outbreak is underway, the model treats all lands as if they

are "protected" (no budworm-caused tree mortality), even though no protection program is applied.

Forest Types

The next major division of land is between softwood and mixedwood forest types, which are defined on the basis of the relative stocking of hardwood (nonhost) species. In Maine, stands with more than three-fourths of the total stand volume in coniferous species are classified as "softwood." Species composition usually is some mixture of spruce and fir, though some stands dominated by northern white cedar (*Thuja occidentalis*) also are included in this type. In mixedwood stands, the softwood component usually ranges from one-fourth to three-fourths of total stocking. Stands with less than 25 percent of the volume in softwood are typed as hardwood stands and are not a part of the resource simulated by the model.

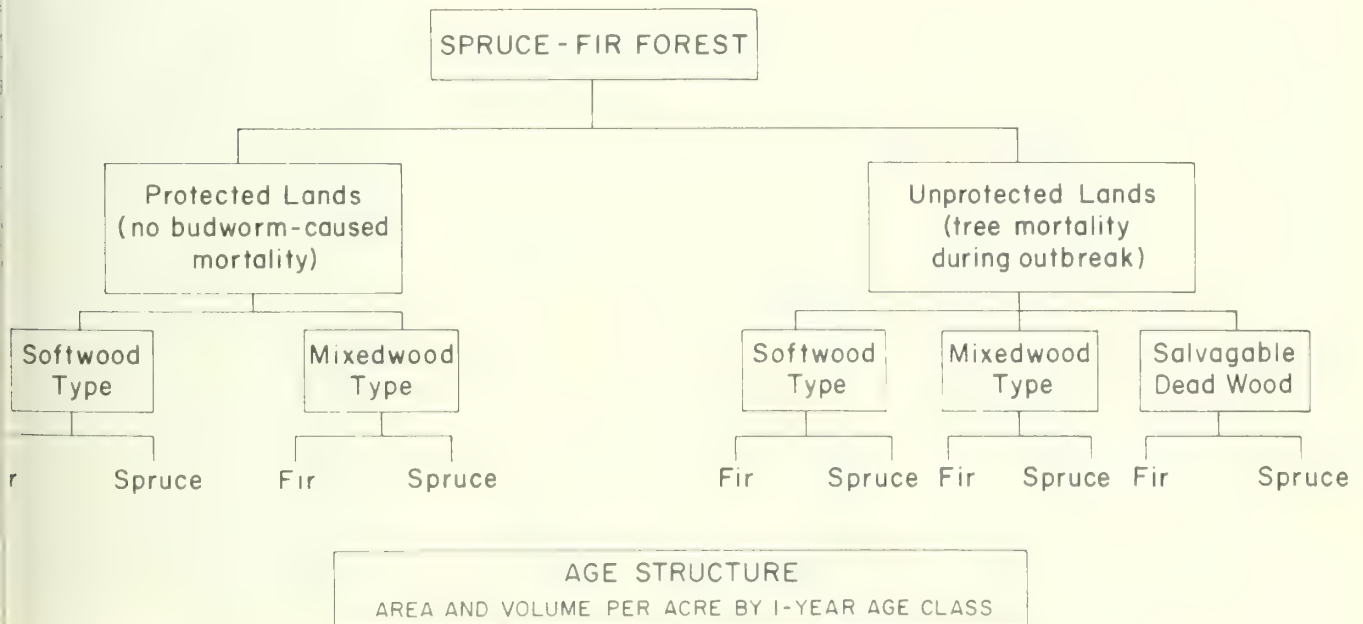


Figure 2.—General structure of a spruce-fir forest as represented by the Green Woods Model.

Though the exact definitions may be somewhat arbitrary, the distinction between softwood and mixedwood types is valuable for modeling purposes. Softwood and mixedwood stands differ in site quality, growth rate, vulnerability to budworm damage, and ease of regeneration, and usually are managed differently as a result. Separating softwood and mixedwood areas in the model allows the forest dynamics to be modeled more accurately. Also, because these types are readily distinguished on aerial photos, maps prepared on this basis generally are available for most large landholdings in the spruce-fir region, and forest inventories usually have been stratified on a forest-type basis. Thus, the basic resource data needed to run a simulation already are available to most managers of spruce-fir forests.

Age Structure

The next major division of the forest, and the key to the way it simulates forest dynamics, is the distribution of area by age class. All processes affecting forest development and management are modeled on the basis of age. Rates of growth and vulnerability to budworm damage are specified as functions of age; the major management practices—harvesting and budworm protection—are allocated to particular age classes; and forest regeneration is modeled by removing area from older age classes after harvesting or mortality and adding it back to young age classes the following year.

Because some (Westveld 1953) have recommended silvicultural systems based on an uneven-age model of stand development, the choice of an even-age paradigm for modeling spruce-fir forest dynamics merits further discussion. Overwhelming historical evidence (Mott 1980) and studies of stand development (Baskerville 1965, 1975; Mott 1976; Seymour 1980) indicate that the current spruce-fir forest originated from

heavy disturbances that operated on a scale much larger than individual trees within stands. Logging of the virgin red spruce from 1870 through the 1920's, the intense spruce budworm outbreak of 1912-20, and periodic destructive windstorms and bark beetle outbreaks removed the mature forest over large areas essentially at once. Stands that regenerated afterward have developed in distinct phases characteristic of even-aged forests: an early period when trees gradually occupy the site; a period during midlife when height growth accelerates and merchantable volume accumulates rapidly as trees cross the ingrowth threshold; a period during maturity when height growth slows, no new recruitment occurs, and volume growth is limited to accretion in diameter; and finally, if no harvesting or budworm attack occurs, a period of overmaturity when natural mortality may exceed accretion and net growth becomes negative. Although widespread application of partial cutting has obscured this pattern in some cases, a consensus clearly has emerged that the present spruce-fir forest is more naturally even-aged than otherwise.

As used in the Green Woods model, age classes are actually stages in stand development. Exact biological age is not crucial. Once a simulation is underway, "ages" of the various strata are really indexes of the time elapsed since the beginning of the run. Similarly, for stands regenerated during a simulation, "age" is an index of time elapsed since harvesting or budworm-caused mortality.

Species Composition

The final major division of forest land is between the two major hosts of the budworm—balsam fir and spruce. The spruce component in Maine, for which the model was developed originally, is primarily red spruce, but other spruce species could be used. There are important differences between balsam fir and spruce in

growth, longevity, regeneration, and vulnerability to budworm damage. Maintaining separate areas for spruce and fir in the model allows the user to vary these processes in accordance with local experience or published information.

In the model, the total area in each age class is allocated to spruce or fir in proportion to the relative stocking of each species. In terms of simulating forest dynamics, these "model areas" are treated as pure "stands" of spruce or fir, even though no actual stands are recognized. The model grows, kills, and regenerates spruce or fir areas on the basis of age and forest type only. The relative species composition of the affected age class is not a controlling factor.

Conceptually, these spruce or fir "model" areas represent areas of the real forest occupied by spruce or fir trees. Areas defined in this manner are artificial only in the sense that they cannot be tied directly to a stand type map. Thus the difference between "real" and "model" areas is simply a matter of scale. Because the model does not attempt to simulate individual stands, this is not a serious deficiency. The purpose of this model is to replicate spruce-fir dynamics and management practices on a forestwide basis. This simple structure eliminates the need to keep track of areas in particular species mixtures, with little loss in realism in simulating natural forest-level dynamics.

The primary situations where the true, mixed composition of spruce-fir stands must be recognized explicitly are in the application of management activities—timber harvesting and budworm protection—which are applied to "real" acres. In both of these instances, mechanisms are provided for generating realistic proportions of spruce and fir in the volumes harvested and acres protected.

Stocking

Once its area structure is defined, the forest is stocked with merchantable cubic volume. In general, this is done by supplying the model with the average volumes per acre by age class for each of the four major divisions of forest area (one each for fir and spruce in both the softwood and mixedwood types). Total forest volumes are obtained by multiplying areas by volume per acre for each species and age class, then summing over all age classes.

Algorithms Used to Define Initial Forest Structure

To define the forest structure, the total area in both the softwood and mixedwood type is distributed to age classes. Although 1-year classes are maintained internally, data are input by 10-year classes for convenience. Up to 15 classes can be specified, with the oldest area in the 141-150 age class. Softwood and mixedwood types can have separate age-class distributions.

After the area is distributed by type and age class, two options are available for defining the initial stocking levels and the proportions of spruce and fir in the forest. Volumes per acre can be input as a percentage of Meyer's (1929) normal yield tables or directly as per-acre volumes by species, depending on the nature of the data available to the user.

Percent-of-normal stocking option.—Under the Meyer percent-of-normal stocking option, stocking for each 10-year age class is specified as a proportion of the merchantable volumes given in Meyer's (1929) normal yield tables. Stocking percentages are given separately for each forest type by 10-year age class. A Weibull distribution function fitted by nonlinear regression to Meyer's data for Site Index 50 (softwood type) and Site

Index 60 (mixedwood type) is used (Appendix I). Figure 3 shows the volumes per acre obtained when 50 percent stocking is used for all age classes in the softwood type and 30 percent is used for mixedwood.

After total stocking is defined, areas and volumes are allocated to individual species. Separate arrays are used for both the softwood and mixedwood types correspond to those used for the age-class distribution and stocking. The user specifies the percentage of each 10-year age class that is occupied by fir. This should be done on the basis of how much area actually is occupied by each species, regardless of whether they are in pure or mixed stands. Obviously, measuring these areas directly on an individual-tree basis is not feasible, so an alternative approach is used.

According to Meyer (1929), volumes of fully stocked "normal" stands of pure red spruce and pure balsam fir are quite similar at the same age. This suggests that spruce and fir are close substitutes for each other in terms of growth and yield. Thus, over an entire forest, the volumes of fir and spruce that accumulate in a given age class should bear a direct relationship to the areas actually occupied by each species. For age classes with merchantable volume (those over 25), the relative volumes by species are used to apportion areas.

Age classes under 25 have no volume in the model, so areas must be assigned directly on the basis of the expected proportion of fir and spruce when the young areas reach merchantable size. These data should be consistent with the

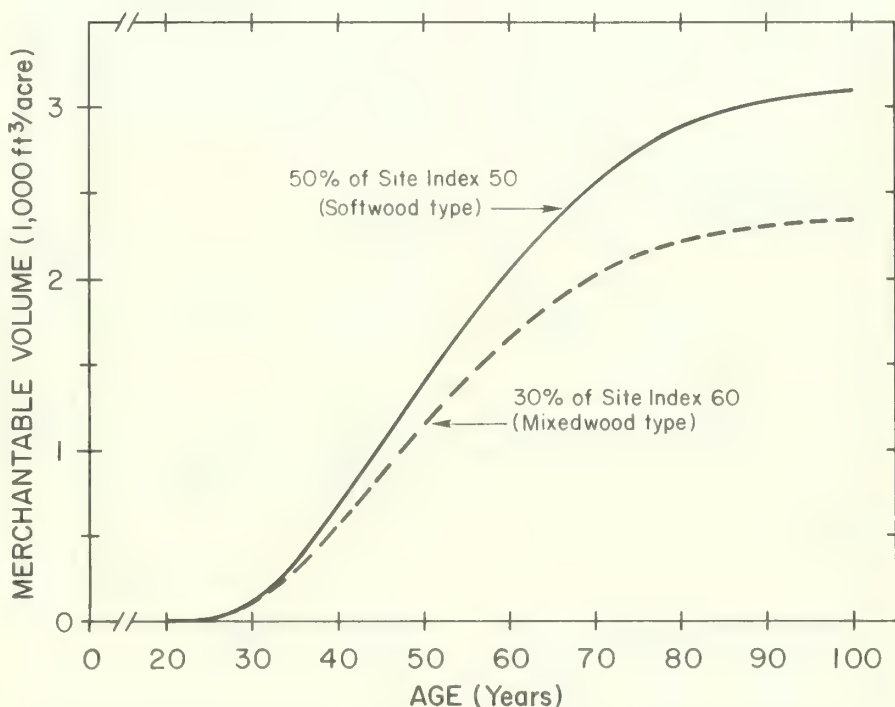


Figure 3.—Merchantable yield of spruce-fir, by age, for selected cases (calculated from Weibull function fitted to Meyer's normal yield tables, Appendix I).

assumptions used to determine the species composition of the regeneration, but are not necessarily the same as the stocking on regeneration plots taken immediately after logging. Stand composition may change by the time trees reach merchantable size, either due to differences in natural development or because early density-control treatments were applied to favor one species. Unlike the real world, species composition in the model is fixed until the areas are old enough to be affected by harvesting or budworm mortality. Therefore, composition of the unmerchantable age classes must reflect the end result (at age 25) of these early stand dynamics, not the initial condition.

User-supplied stocking option.—If inventory data are available with volumes of spruce and fir by age class, these can be specified directly by the user, eliminating the need to determine normal-stocking and fir percentages. When this option is selected, users input the actual volumes per acre by species and 10-year age class for both forest types. The program then automatically calculates the proportions of spruce and fir, and distributes the area within each age class accordingly.

Volumes per acre of a particular species taken from inventory data apply to the entire area in the age class ("real" areas), not just to the area actually occupied by that species and no others (represented by the pure-species "model" areas). Thus, spruce and fir stocking levels obtained from inventory data are converted by the model to hypothetical pure-stand stocking.

Actual volumes per acre are multiplied by the factor TA/SA , where TA equals to the total area in the age class and SA equals the area allocated to the particular species (fir or spruce). In effect,

there is higher stocking on fewer acres, but the same total volume results over the entire area in the age class. Since age classes below 25 have no volume, those must be allocated explicitly as in the normal-stocking option.

Because these pure-species model areas (the SA 's) are determined by the relative volumes per unit area, calculated stockings of spruce and fir *expressed on a model-acre basis* are equal with this procedure. Thus, different total volumes in an age class result entirely from having different total areas occupied by each species. These assumptions initially may confuse users who select this option to stock their simulated forest, but it is simply the logical outcome of the fact that spruce and fir essentially are equally efficient in growth per unit area.

Examples presented in the section on applying the model show these processes in detail. The following example compares the normal-yield function and user-supplied stocking algorithms for defining initial forest structure:

Both Options

User provides:

1. Total type area = 1,000 acres
2. Proportion of area in 51- to 60-year-old stands = 0.10

Model calculates:

1. Area in 51- to 60-year-old stands = $0.10 \times 1,000 = 100$ acres
2. Area in each one-year class = $0.1 \times 100 = 10$ acres

Normal Yield Function Option

User provides (for each 10-year age class):

1. Proportion of normal stocking = 0.50
2. Proportion of age class in fir = 0.40

Model calculates:

1. Volume per acre = $0.50 \times 2,911$ (Age 51, from Appendix I) = 1,460 ft^3 per acre
 2. Area in fir = $0.40 \times 10 = 4$ acres
 3. Area in spruce = $10 - 4 = 6$ acres
- (Note: Each 1-year, internal age class has a different stocking under this option.)

User-Supplied Stocking Option

User provides (for each 10-year age class):

1. Fir volume per acre = 584 ft^3
2. Spruce volume per acre = 876

Model calculates:

1. Total volume per acre = $584 + 876 = 1,460 \text{ ft}^3$
2. Proportion of fir = $584/1,460 = 0.4$
3. Area in fir = $0.4 \times 10 = 4$ acres
4. Area in spruce = $10 - 4 = 6$ acres
5. Volume of fir on model "fir acres" only = $\frac{584 \times 10}{4} = 1,460 \text{ ft}^3$
6. Volume of spruce on model "spruce acres" only = $\frac{876 \times 10}{6} = 1,460 \text{ ft}^3$

(Note: All 1-year, internal age classes within the 10-year class have the same stocking under this option.)

Natural Processes of Forest Development

Forest Growth

The rate at which the simulated forest grows is determined by age, species, and forest type, and may be reduced for the effects of budworm defoliation differentially on protected and unprotected lands. Growth rates can be specified directly on a per-acre basis by species and age class, or can be calculated from an optional mathematical function. The function currently programmed is a Weibull formulation of Meyer's (1929) normal yield tables, but any function can be accommodated. Additional flexibility is provided by user-controlled adjustment factors specific to each species and forest type, which raise or lower growth rates proportionally over all age classes. In this manner, the user can specify both the *shape* and *level* of the growth function, which facilitates the process of calibrating the forest to reproduce historical patterns. Another possible use would be to predict the results of management practices designed to increase growth rates on particular components of the forest.

Use of a *growth* function to simulate forest development allows the major influences to be applied annually, in any combination, and at rates which can vary over time. The forest can "react" dynamically to each; the resulting structure is the logical accumulation of these perturbations. For predicting and analyzing budworm impact, this is a major advantage over models based on yield-table projections. The latter track stand development for an entire rotation in advance, and can be too rigid to simulate these processes unless "defoliated" strata are redefined during a simulation.

Growth rates used as model inputs are modified *net* growth rates. They are intended to represent ingrowth plus accretion minus normal (noncatastrophic) mortality only. Budworm-caused mortality is calculated and applied separately. The net growth of the entire forest computed by the

model is a true net growth, including the effect of budworm-caused mortality, if any.

In the model, forest growth is the result of two distinct, independent processes which occur annually during a simulation. First, the forest is "aged" by advancing the age-class distribution (which is maintained internally by 1-year classes) by 1 year. Areas removed from older age classes by harvesting or budworm mortality are added back to the first age class to simulate regeneration. Second, stocking levels are updated annually by adding the net annual growth to the year-end volume per acre of the previous (1-year younger) age class. For a particular age class, the product of these two variables—area times volume per unit area—gives the total volume in that class. "Growth" is the difference between the new and previous total volumes, summed over all age classes for each type, before harvesting and budworm mortality take place.

Growth function option.—Non-linear regression was used to fit a Weibull distribution function to Meyer's (1929) normal yield table (Appendix I) for Site Index 50 (used for the softwood type) and Site Index 60 (mixedwood type). Site index from Meyer's tables is the height of dominant spruce at a total age of 65. Because the model requires annual growth, not yield, the equivalent Weibull density function (i.e., the derivative of the distribution function, with the same parameters) is solved repeatedly to obtain growth rates for each age class.

Meyer's tables predict growth for fully stocked "normal" stands, and usually must be reduced to match observed growth on large areas that are less well stocked. Four user-supplied calibration factors, one each for fir and spruce in both the softwood and mixedwood types, reduce or increase the level of the growth function proportionately over all age classes. Figure 4 shows the growth rates predicted

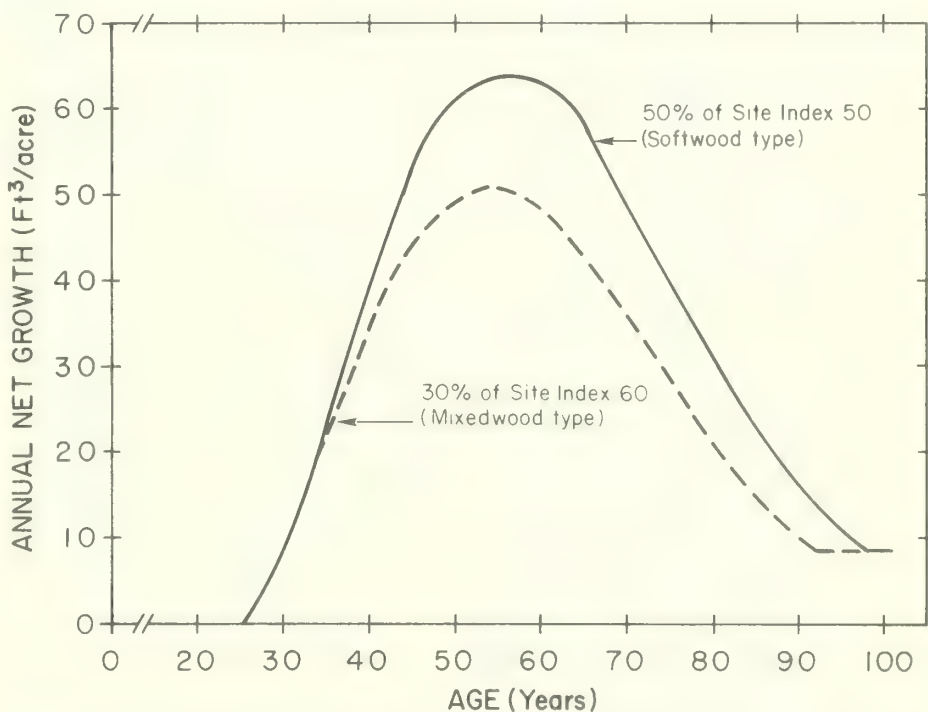


Figure 4.—Annual growth of spruce-fir, by age, for selected cases (calculated from Weibull density function fitted to Meyer's normal yield tables, Appendix I). Rates do not include allowances for mortality caused by the budworm or old-age, which are applied separately.

using 50 percent of Meyer's values in the softwood type and 30 percent in the mixedwood type.

Growth rates from the unmodified growth function for normal stands approach zero as full site occupancy is reached at older ages. This probably is not realistic for stands of below normal stocking, so simulated growth in older age classes is not allowed to fall below 8.5 ft³ (0.1 cord) per acre per year. Calibration factors modify this rate by species and forest type, as described previously.

Old-age fir mortality.—Meyer's tables show that yields of red spruce and fir are similar, so the same function is used to compute growth for both species. However,

yield tables for the Lake States (Gevorkiantz and Olsen 1950) and studies of old-growth fir stands in New Brunswick (Baskerville 1965) show that stands of fir begin to break up from natural causes beyond age 70. Seegrist and Arner (1982) also present conclusive evidence that fir has a much higher probability of dying from natural causes than spruce, especially in the larger diameter classes. Most mature firs are severely weakened by heart rot and tend to break off or uproot in windstorms, resulting in mortality which exceeds accretion. To simulate this process, an "old-age" mortality function (Fig. 5, Appendix I) can be applied annually (at the user's option) to "kill" varying proportions of the fir volume over age 50.

Meyer's tables are gross volumes (inside bark) for all trees and above the 4-inch d.b.h. class. Maine, merchantable volumes are more typically calculated only for 5-inch and larger trees, including bark, and may have deductions for cull applied differentially by species. As a result, Meyer's functions may predict growth rates that are too high in young age classes dominated by 4-inch trees, and may overestimate growth for old balsam fir if the old-age mortality option is not applied. If a more appropriate growth function is available to the user, this could be substituted for Meyer's equations by simple changes in a program subroutine. The same percentage adjustments could still apply to this new function, which facilitates calibrating simulated growth rates to agree with observed ones.

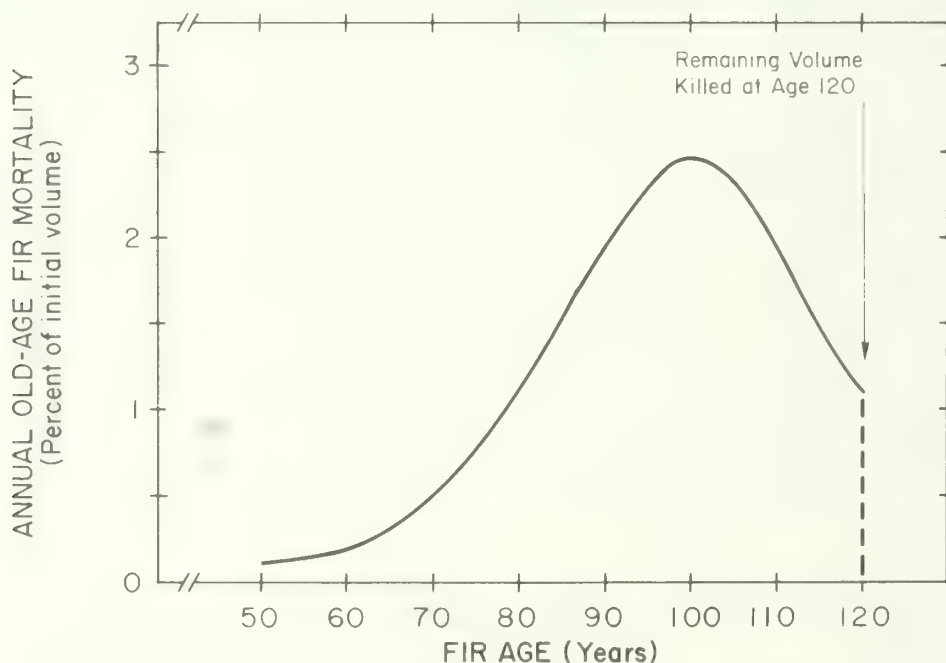


Figure 5.—Optional old-age mortality function for balsam fir (Appendix I).

User-specified growth rates.—Instead of using a function to predict growth, users can input their own growth rates directly. This allows an empirical growth function to be constructed with data from remeasured plots that have been stratified by age class. Under this option, net growth (in $\text{ft}^3/\text{acre}/\text{year}$) is specified separately for fir and spruce for the following age groups: 25–30, 31–50, 51–70, 71–90, and 91–150. Stands under age 25 grow no merchantable volume in the model. These rates should include all mortality except that caused by budworm. If the old-age fir mortality function is used, mortality of fir due to wind breakage and blowdown also should be excluded.

As with the Meyer option, the same four adjustment factors can be invoked to make the growth of the simulated forest agree with observed trends. If growth data are derived directly from the forest being simulated, no adjustment should be required, i.e., all factors should be 100 percent. The old-age fir mortality function also can be applied as an option depending on whether the specified growth rates for old fir include mortality. If the growth rates for fir age classes over 90 include all mortality (except budworm caused), old-age mortality should not be applied.

When the model calculates growth and adjusts per-acre stocking, volume is added separately to the pure-species (fir or spruce) "model" acres, not to the entire area in the age class. Therefore, user-supplied growth rates, expressed on the basis of real (not model) acres, must be adjusted to make them compatible with the model-based rates. This is done as follows: the user-supplied growth is multiplied by the factor TA/SA , where TA equals the total area in the age class (by forest type) and SA equals the area allocated to the particular species (fir or spruce). In effect, there is a higher growth rate on fewer acres, but the same total growth results over the entire area of the age class.

When Meyer's function is selected, the rates calculated already are on a pure-species basis, so no adjustment is needed.

Forest Regeneration

Regeneration is modeled by transferring the areas removed from older age classes (through harvesting or budworm-caused tree mortality) to the young end of the age-class distribution. During this transition, a number of things can happen: areas can change forest type, regeneration can be delayed, or the relative spruce-fir composition of the new age class can be altered. These dynamics are specified entirely by the user on the basis of actual regeneration patterns observed on the forest being simulated.

Areas that originate from simulated harvesting operations are accumulated into two "pools," one for each forest type. Softwood areas can be converted to mixedwood land, which has the effect of reducing the spruce-fir productivity of these acres when they become merchantable at age 25. This is designed to model the component of the real forest where, for whatever reason, long-lived hardwood species become a permanent part of stand composition after harvesting on what was formerly pure spruce-fir land during the previous rotation. Mixedwood cutovers also can be converted to the hardwood type to model the well-established difficulty of regenerating spruce and fir in stands with a strong hardwood component (Westveld 1931). Because the hardwood type is not simulated by the model, these areas are effectively lost from the spruce-fir resource base. Both processes are controlled by specifying separate proportions of the total cutover area in each type that are to be converted annually.

Once the forest-type distribution of the regenerated areas is determined, specified proportions of each can be forced to undergo a simulated regeneration lag. The

duration of the lag period (which can range from 1 to 30 years) and the proportion of the total cutover area to be lagged, are specified separately for each type.

From the standpoint of the model, lag periods are the "extra" time after harvesting that is required for the regenerated areas to become synchronized with the developmental track defined by the growth function. In effect, areas undergoing a lag have "negative" ages. For example, assume the growth rate for 31- to 50-year-old fir is set at 50 $\text{ft}^3/\text{acre}/\text{year}$, but that 40 percent of the stands cutover in 1950 do not begin to grow at this rate until 1990, not 1980 as predicted. This can be modeled by specifying a 10-year lag on 40 percent of the acreage. In effect, the lag period allows the stand establishment period to deviate from the "normal" pattern on a certain percentage of the forest, to reflect regeneration failures, effects of competing vegetation, and other factors that are not simulated directly.

When regenerated areas are added to the first age class, either immediately or after undergoing a lag, the relative amounts that become fir or spruce "model" acres are specified by the user. Specifically, the value needed is the proportion of the total regenerated area that is fir; the balance automatically becomes spruce. The same value applies to both the softwood and mixedwood types.

These regeneration processes are primarily natural ones, but can be altered substantially by cultural practices such as cleanings, precommercial thinnings, or herbicide spraying. The assumptions used must mimic the net effects of both natural development and cultural practices on the species composition and stocking when stands reach merchantable size. Thus, the correct input is the expected composition at age 25, not the stocking immediately after harvesting.

Regeneration after budworm-caused mortality is treated differently from that originating after simulated harvesting. Unlike cutover areas, stands killed by the budworm regenerate in a predictable manner. Advanced regeneration, established during the years preceding the outbreak, is not physically affected by budworm attack (as in logging) and tends to retain control of the site after the overstory trees are killed (Ghent et al. 1957; Baskerville 1975). In the model, budworm-regenerated areas remain in the same species and forest-type categories, and do not undergo a lag. If the budworm-caused mortality process were altered such that areas were removed from age classes below 50, this algorithm also would need to be changed to allow more flexibility in the way these areas are handled.

In general, the protection status of regenerated acreage is the same as that of parent stands, that is, areas harvested from protected lands remain under protection after regenerating, even though they probably would not need to be sprayed until later in their development. An exception to this rule is made if no protection is specified for the 0-40 age classes; in this case, all regeneration is added to the unprotected lands. By definition, all budworm-killed areas originate from unprotected land, and regenerate into this category.

Once specified, all parameters controlling regeneration apply without change over the entire simulation. Areas can be added to the resource base by simulated conversion of nonhost (no spruce-fir) forest types. This is accomplished by "planting" a fixed number of acres per year with pure spruce. When these acres become merchantable at age 25, they will grow at the same rate as "natural" spruce areas, as specified by the growth function. All planted areas are regenerated into the protected lands if an outbreak is underway.

If data were available, a more realistic model could be constructed in which these processes vary as functions of the particular harvesting strategies used. For example, advanced regeneration in younger stands, especially of spruce, frequently is insufficient to regenerate a fully stocked stand after clearcutting. To simulate this process accurately, the percentage of the harvested area that undergoes lag, as well as the percentage of fir in the regeneration, could be increased as the age of the stands cut becomes younger.

Effects of Budworm Attack

The Green Woods Model does not simulate the actual dynamics of spruce budworm populations. The timing and severity of outbreaks are specified by the user on the basis of current or expected trends. The model predicts only the major effects of budworm defoliation—tree mortality and growth reduction—on the evolving forest structure.

When a simulated outbreak begins, a protection strategy must be specified. This partitions the forest into two categories: protected lands on which there is no tree mortality, and unprotected lands where tree mortality begins after a specified lag period. Growth reduction also begins at rates that can vary between protected and unprotected components of the forest.

Tree mortality.—Studies of outbreaks reviewed by MacLean (1980) and historical records for Maine (Seymour 1980) show that tree mortality from uncontrolled budworm outbreaks can vary by host species, forest type, and stand age. The model is structured so that survival on unprotected lands can be specified separately for each of the 12 components of the forest:

Age class	Softwood type		Mixedwood type	
	Fir	Spruce	Fir	Spruce
0-40	—	—	—	—
41-70	—	—	—	—
71+	—	—	—	—

These categories correspond directly to those used to allocate forest protection. The survival rate is the percentage of each category the user expects to be alive after budworm-caused mortality is finished.²

Because the budworm feeds primarily on current foliage of fir and spruce, tree mortality is a gradual process that extends over many years, as old foliage is consumed or lost to natural attrition and is not replaced. This is modeled by distributing the total mortality (given by the user-supplied survival rates) over a 6-year period according to the following annual rates:

Year of sequence	Proportion of total mortality (unadjusted)	Adjusted mortality for previous year
1	0.05	0.05
2	.10	.105
3	.20	.235
4	.25	.385
5	.30	.750
6	.10	1.000

² An earlier version of the program used four reverse logistic equations to predict mortality by species and forest type as a function of age. Severity factors were used to calibrate these functions, but recent tests have shown them to be too restrictive, primarily because they cannot be made to predict the high mortality rates that have been observed in young stands during the current outbreak.

In stands not previously attacked by the budworm, trees begin to die 3 to 5 years after the onset of defoliation (Belyea 1952; Blais 1958; Baskerville and MacLean 1979; Maclean 1980). However, this lag period may be substantially shorter for trees removed from protection that do not have a full complement of foliage. In the model, the time between the onset of the budworm outbreak and the first year of tree mortality on unprotected lands can range from zero to 5 years. Separate mortality lag periods can be applied to spruce and fir, and can be changed each time lands are withdrawn from protection.

The actual mechanism used to simulate mortality depends on the age of the affected areas. In age classes over 50, areas are "killed" by removing them from the vulnerable age classes and "regenerated" by adding them back to the first age class the following year. The scale and spatial distribution of mortality are not modeled explicitly. Simulated budworm-caused mortality removes area formerly allocated to the dead mature trees and transfers it to 1-year-old advanced regeneration that begins to grow normally. In effect, this creates two age classes (the survivors and regeneration) where only one existed prior to the budworm attack (Shent et al. 1957). The volume lost to mortality is calculated by multiplying the area killed by its corresponding stocking per acre. Thus, in age classes over 50, the proportions of the area and volume killed are equal, which leaves the surviving model area stocked at the preoutbreak level.

In younger spruce-fir stands, budworm mortality has somewhat different effects. Advanced regeneration is less abundant or might be totally deficient. Due to the lower vulnerability of young trees, only a portion of the overstory might be killed. Unless it is unusually severe, budworm mortality in these age classes resembles a

heavy thinning; the surviving overstory is understocked, but no new age classes are regenerated (Baskerville and MacLean 1979). This is modeled by removing only volumes from age classes below 50 in which there was budworm mortality; areas are unaffected and continue to advance in age. Because less volume remains on the same area, stands in these age classes become understocked. Although growth may return to preoutbreak rates after mortality is complete, this understocking persists until the age classes are harvested.

This algorithm for simulating mortality is not without certain deficiencies. Because all age classes under 25 have no merchantable volume, they are essentially immune to budworm effects. Experience from the current outbreak shows that stands in this age class can suffer high mortality if defoliation persists for a sufficiently long period. Also, the threshold of age 50 for determining whether areas regenerate after budworm mortality is somewhat arbitrary. In practice, this would be affected by past silvicultural treatments and the current stocking of the younger age classes. The model could be modified to remove area from *all* age classes after mortality, or perhaps more appropriately, to put all areas lost to mortality from young age classes through a regeneration lag. The basic problem here is not the inadequacy of the model to mimic the real world, but a lack of research and experience to describe the underlying dynamics.

In the model, areas that survive the 6-year sequence of tree mortality cannot sustain another tree-killing outbreak for the remainder of the simulation. This feature was incorporated on the grounds that a single outbreak usually would purge the unprotected forest of its vulnerable components, rendering it invulnerable to further tree mortality. This may not be realistic for stands that are attacked by the budworm when young and again during

a second outbreak much later in life. Clearly, most if not all of the trees over 70 years old in the present spruce-fir forest survived the 1910-20 outbreak; many of these same trees, especially the older fir, are now being killed in the current outbreak. However, this does not prevent a realistic simulation of mortality in the current outbreak, because the model does not "know" that these older stands have a history of budworm attack. It would effect only the vulnerability of the now young age classes to an outbreak that might occur during the 21st century.

Because areas that have survived tree mortality are stored separately in the program, this algorithm could be changed to allow areas to experience multiple tree-killing sequences. A provision could be added to transfer areas formerly attacked by the budworm to the vulnerable components of the forest, perhaps only after a minimum period of years had elapsed since the previous outbreak.

Growth reduction.—Forest growth can be reduced to account for the effects of budworm defoliation. Four user-supplied factors—one each for fir and spruce on both protected and unprotected lands—are used to reduce growth proportionally over all age classes. Growth reduction begins automatically 2 years after the onset of an outbreak, and continues for a period which can vary among these four components of the forest. After mortality on unprotected lands is complete, growth reduction can still be applied. With this provision, users can simulate reinfestation from surrounding protected lands, or model the effects of understocking (resulting from mortality)

Forest Management Practices

which reduces growth in surviving uninfested stands.³

Because the model uses *net* growth rates (including negative effects of natural mortality), growth-reduction factors have a different interpretation between protected and unprotected lands. The appropriate factors for *unprotected* fir and spruce should include only the effects on surviving trees; budworm mortality is simulated separately as described previously. Specifically, the correct input is the difference between the actual accretion of surviving trees and the rates expected under normal (nonoutbreak) conditions.

Insecticide spraying usually protects sufficient foliage to prevent widespread tree mortality, but there still is some defoliation that can reduce growth (Kleinschmidt et al. 1981). On protected lands in the model, no budworm-caused tree mortality is simulated, so the appropriate reduction factors must take into account both lost accretion and any net increase in tree mortality due to budworm defoliation in the protected stands.

Forest Protection Against Budworm

The goal of forest protection is to prevent or limit the destructive effects of uncontrolled budworm outbreaks. In the model, different levels of forest protection can be allocated to each forest type and species, and to age classes 0–40, 41–70, and 71+. By protecting various proportions of the total forest area in each of these categories, the user defines a “protection zone” where there is no budworm-caused tree mortality and growth reduction can be less severe than on the unprotected lands.

Although protected and unprotected lands are often combined in model output, all attributes of forest area are stored internally in separate arrays for each. These characteristics evolve independently in response to the user-controlled dynamics of a particular simulation. As a result, protected and unprotected lands develop unique age structures, stocking levels by age class, and forest type distributions.

A protection strategy is needed only if a simulated outbreak is underway. Once a protection zone is specified during an outbreak, tree mortality begins on the remaining (unprotected) area. Protection strategies can be changed up to six times during a simulation, to withdraw area from or add it to the protection zone. If changes result in a net reduction in protected acreage, areas are transferred to the unprotected category and tree mortality begins soon thereafter according to the specified lag period.

Through successive reduction in the protection zone, areas can be at different stages of deterioration in the 6-year mortality sequence. The protection zone can be increased during an outbreak only if unprotected acreage is available which has not passed the third year of mortality. When such an increase is specified, the mortality process is halted, and the area is transferred to the protection zone. Areas beyond the third year of mortality are assumed to be too badly deteriorated in tree condition to recover, and cannot be retrieved.

With the current state of the art, protecting the spruce-fir forest against the budworm is accomplished almost entirely by annual insecticide spray programs. Current protection strategies are designed primarily to prevent tree mortality, which usually does not require that all infested areas be treated annually. The protection zone, as defined by the user, is intended to represent the total area where such programs are applied successfully, plus any uninfested areas where it is not needed—the total area on the forest in which there is no budworm-caused mortality. Thus, the area in the protection zone bears no direct relationship to the acreage sprayed annually, which is determined by the particular status of budworm populations and tree condition in a given year. For example, if it is determined that, on average, areas need to be sprayed every other year to prevent mortality, then the protection zone would be twice the size of the average annual spray program.

³ There are two important differences between this algorithm and the previous version of the model in use during 1980–81. Formerly, growth reduction continued indefinitely on all lands so long as some acreage remained under protection. The new feature was incorporated to allow a simulated “collapse” of budworm populations. Also, in the old version, growth on unprotected lands after tree mortality was complete was automatically reduced at the same rate as the protected lands, subject to a function that weighted growth according to the proportion of the total forest under protection.

Targeting protection.—In practice, aerial spraying is applied to “real” forest acres, not to the pure-species areas used by the model. Within each forest type, the spruce and fir areas targeted for protection must be specified in proportion to their volumes per acre to reflect the species composition of stands in the protection zone. Targeting on one species to the exclusion of the other can still be done, but not to an intensity beyond that which can be achieved with the smallest operationally feasible spray block. For example, specifying a protection zone that includes only fir is not a feasible strategy; in the model this would represent a situation where all fir trees were sprayed but the spruce trees in the same stands were not. In practice, protecting the desired amount of fir would require spraying stands that also contain some spruce. To account for the way the model simulates growth and mortality, this additional area occupied by spruce trees also must be included in the total protection zone.

Managers usually begin with the total acreage in a protection zone, then work backward through a stand-by-stand hierarchy to arrive at the correct proportions of each species to protect in a simulation. Details of this process are shown in the section on applying the model.

Timber Harvesting

The algorithms used to simulate harvesting can replicate

virtually any operational strategy. Users control the following variables, singly or in combination:

1. Total volume harvested.
2. Percentage of spruce or fir in the total cut.
3. Percentage of the total cut to come from dead trees (salvage).
4. Percentage of the total cut to be allocated to protected or unprotected lands.
5. The age of the youngest trees considered merchantable for both spruce and fir.
6. Intensity of discrimination against the oldest wood within the merchantable age classes.

Harvesting strategies can be changed annually, up to 30 times during a simulation.

The total volume of spruce and fir to be harvested is specified in merchantable cubic feet, with no distinction by size or product class. This allowable cut should equal the total drain from the merchantable spruce-fir inventory that results from all harvesting operations; the portion actually utilized is not relevant.

If a budworm outbreak is underway and some lands are under protection, users can target simulated harvests onto protected or

unprotected lands by specifying the percentage of the total volume to cut from the unprotected acreage.

Species discrimination.—Harvests can be targeted on spruce or fir to simulate strategies that attempt to exploit the differences in growth or vulnerability between these species. We define discrimination “against” fir, for example, as a strategy that attempts to accelerate the harvest of fir to favor spruce and increase its overall composition in the forest. Such discrimination against one species can be accomplished in two ways: (1) clearcuts targeted on stands dominated by one species, bypassing stands of the other; (2) partial cuts that remove primarily one species, leaving residual stands dominated by the other.

Simply specifying the volumes of each species to harvest is not sufficient to define a level of discrimination. Discrimination is a relative phenomenon; it can be defined only by comparing the proportions of each species harvested to their abundance in the entire forest. For example, if 50 percent of the harvest is fir in a forest that also is 50 percent fir, no discrimination is being practiced, since this percentage would arise by allocating harvests entirely at random throughout the forest. However, the same percentage harvested from a forest that is 80 percent spruce would represent an intense discrimination against fir.

In the model, a "no-discrimination" harvesting strategy is defined as one in which the proportion of fir in the harvest equals the proportion of fir in the forest. In Figure 6, this is represented by the 45-degree line (slope = 1.0). Discrimination against a particular species represents the "extra" proportion of that species in the harvest above its share of the inventory. The discrimination factor is defined at the point where spruce and fir make up equal proportions of the inventory (a 50:50 ratio), but is adjusted through an exponential function (Appendix I) to account for the fact that harvest discrimination is more difficult as either species dominates the other. For example, a 15-percent discrimination against fir applied to a forest that is 50 percent fir would generate a harvest of 65 percent (50 + 15) fir. However, in a forest that is 20 percent fir, the same strategy would produce a harvest of 28 percent fir, only 8 percent more than the inventory (Fig. 6).

Merchantability.—With present-day utilization, stands below a certain age usually are regarded as inoperable. Even though they contain trees of merchantable size, the cost of harvesting and subsequent processing outweighs the value of the finished products. Users can simulate these limits by setting a minimum age for operable stands below which no wood will be cut even though volumes are physically present. These low age limits can be specified separately for spruce and fir, and are set once for an entire simulation.

Within the age classes considered operable, users can discriminate against older wood by allocating the harvest to only a specified oldest proportion of the operable inventory. Formally, the discrimination parameter is defined as:

$$\frac{\text{OLDFOR} - \text{YOUNGCUT}}{\text{OLDFOR} - \text{YOUNGOP}}$$

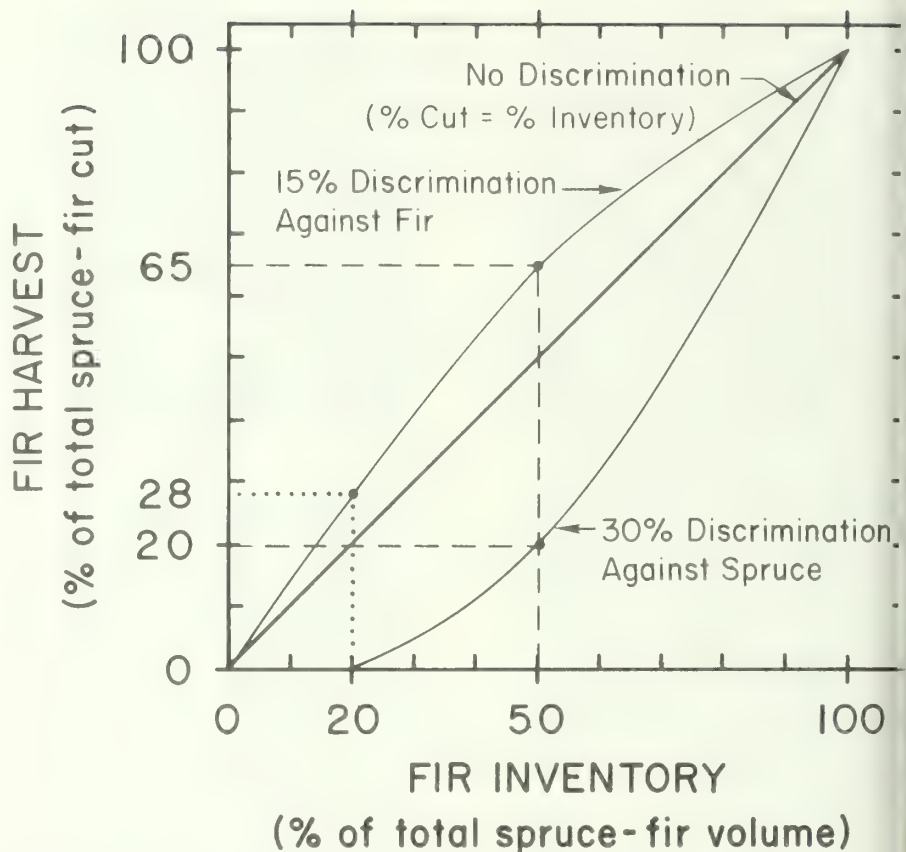


Figure 6.—Schematic of algorithm used to simulate harvesting strategies which discriminate against fir or spruce (Appendix I).

where OLDFOR equals the oldest age class in the forest, YOUNGOP equals the youngest stands considered economically harvestable, and YOUNGCUT equals the youngest stands that a manager initially wishes to harvest, even though younger stands are considered operable and would be cut if necessary. If YOUNGCUT = YOUNGOP, the discrimination parameter = 1.0 and harvests will be allocated uniformly to all age classes above the operable age limit. AS YOUNGCUT approaches OLDFOR, the harvest strategy becomes an "oldest first" rule, with intense discrimination against older wood.

For example, a manager of a forest containing stands up to age 100 determines that the youngest

stands he can harvest are 50 years old, but initially would like to harvest stands only above age 70. To simulate this strategy, he would specify a harvest allocation to 60 percent $[(100-70)/(100-50)]$ of the oldest age classes. As the older stands gradually became exhausted the same percentage would still apply, but over a more limited range of ages. At the point in the simulation where the oldest wood was age 80, the youngest wood harvested would come from age class 62 $[80-0.6(80-50)]$. If insufficient wood is available in the oldest specified proportion to meet the harvest goal, the program continues to accumulate volumes below the calculated age limit, overriding the strategy to avoid a shortfall.

Optimum rotation age and regulation index.—Users specify the optimum rotation age they would employ if the forest were fully regulated by age class. This age is used only to compute an index of forest regulation; it has no role in controlling harvesting operations. The Regulation Index represents the departure of the actual forest structure from the ideal “normal” forest, which contains equal areas in all age classes below the specified optimum rotation age, and none older. It is similar to the coefficient of determination (r^2) used in regression analysis, and is calculated as follows: for each age class, the actual area is subtracted from the expected area in the hypothetical “normal” forest. The absolute values of these differences are summed over all age classes and expressed as a proportion of the total forest area. The resulting index is, in effect, the proportion of the forest that is in the wrong age class relative to the manager’s goals.

It should be emphasized that the optimum rotation age is used only to calculate the regulation index, *not* to control simulated harvesting activities. Actual harvests by age class are governed entirely by minimum operable age and percent allocation to the oldest wood, as described previously; the optimum age is ignored.

Salvage.—During a simulated budworm outbreak, volumes killed in the unprotected lands are accumulated by species and age class into a “pool” that is temporarily available for salvage. Each year, dead wood is “aged” and reduced in volume according to the following factors:

Years since death	Percent of original volume still usable
1	100
2	95
3	85
4	70
5	0

These simulated decay rates were derived from Field and Shottafer

(1979) to account for losses to sap rots, stem breakage in logging and other factors that reduce yields when dead wood is utilized.

Salvage is simulated in two ways: (1) by specifying that a certain proportion of the harvest must consist of dead wood, if any is available, or (2) that dead wood be cut in proportion to its occurrence on the unprotected lands. In the first option, the salvage proportion can be regarded as a goal or a constraint, depending on the needs of the user. Volumes salvaged replace equivalent volumes of “green” wood from the unprotected lands.

Areas harvested and partial cutting.—Simulated harvest areas are equivalent to the actual cutover areas only where operations remove all merchantable spruce and fir trees from the stand (complete clearcuts). If a portion of the total harvest volume is derived from partial cuttings where spruce or fir trees are left in a residual stand, the model will underestimate the actual acreage operated. In the partial-cutting case, the model will remove volume from and regenerate only that portion of the stand actually occupied by trees harvested, not the entire stand area. This has no effect on simulated growth and development of the residual “areas” but does underestimate the actual total area on which operations must be conducted. Volumes removed per acre also will be overestimated by a proportional amount.

The model will reproduce accurate harvested acreages for operations in mixedwood stands that remove all spruce and fir but leave hardwoods. The model does not simulate hardwood trees; the entire area in mixedwood stands is, in effect, allocated to spruce or fir trees by stocking the mixedwood type at lower volumes of spruce-fir per acre. Thus, a given volume of wood harvested from mixedwood land removes more simulated acreage than if the same volume were harvested from the better stocked softwood type.

How the Model Simulates Forest Development

Before applying the model to an actual situation, it might be helpful to illustrate how each of the processes described is simulated by the model. Three examples are presented: Natural growth and development (no cutting or budworm attack), budworm attack at age 60 with no protection, and harvesting at age 60 with a 10-percent discrimination against fir. Each situation begins with a forest composed of 1,000 acres of softwood type, all in a single age class. Species composition was set at 50 percent fir, and simulations are carried out using 50 percent of Meyer’s function to grow the forest. Note how the species composition and age structure of this forest change in response to both natural processes and man’s activities.

Because this hypothetical forest contains area in only one age class, these simulations represent a special case in which the time elapsed since the beginning of the simulation equals the “age” of the forest. In this sense, the 1,000-acre, single-aged “forest” can be considered to be a “stand” whose age is given by the “year” axis. In a realistic simulation of a forest with many age classes, this would, of course, not be true. This example is presented to illustrate how the important dynamics are controlled by age, which is obscured when several age classes are combined.

Natural Forest Development

This simulation begins with 500 fir and 500 spruce “model” acres, all in age class 1. In year 25, growth of merchantable volume begins, with both species growing at the same rate until year 50 (Fig. 7). At this time, the old-age fir mortality function begins to kill small portions of the total fir volume. By about year 70, fir mortality exceeds accretion and net growth on this area becomes negative. The fir area becomes progressively understocked, resulting in a declining yield.

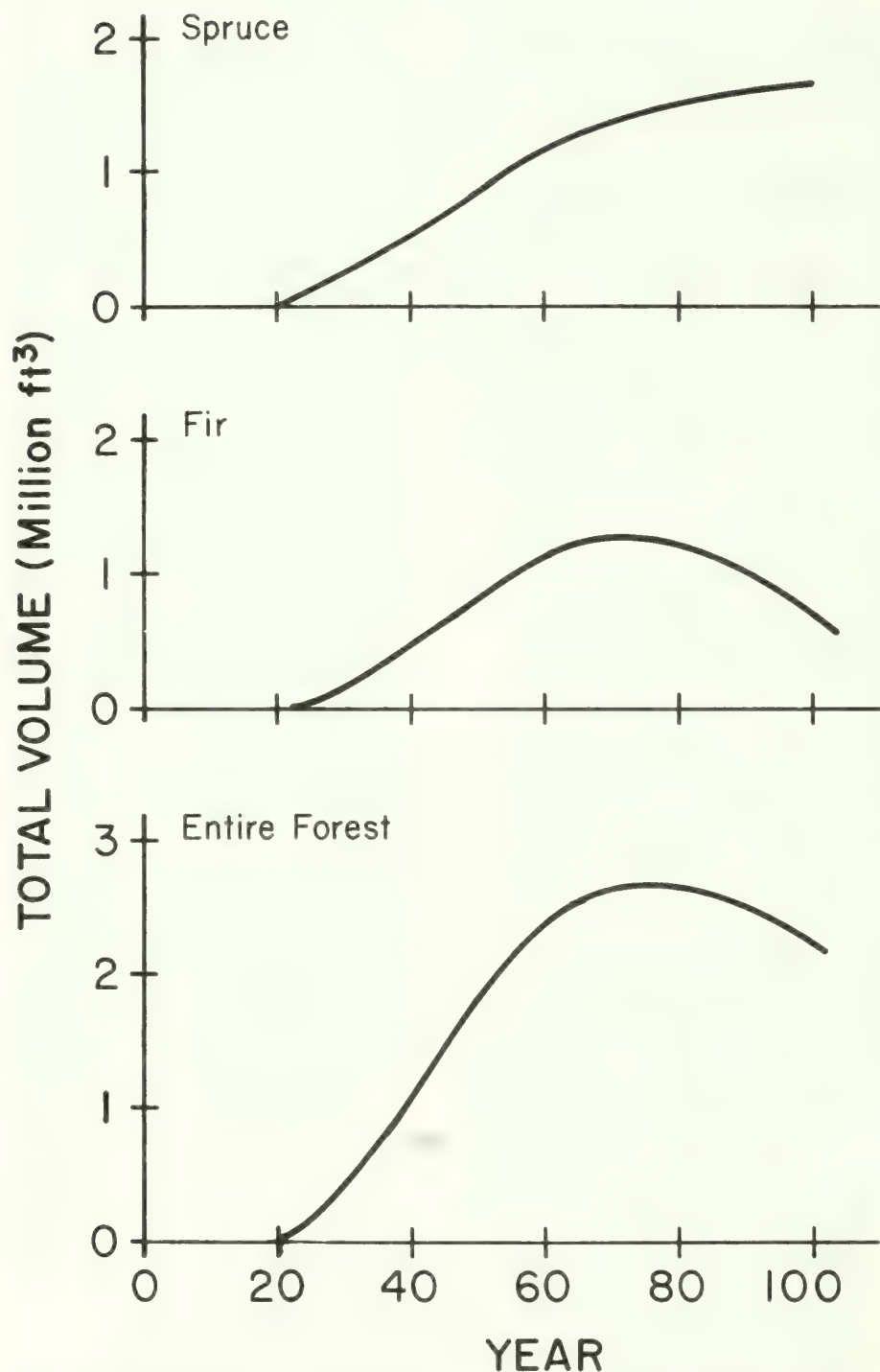


Figure 7.—Simulated growth and development of a hypothetical 1,000-acre spruce-fir forest (50 percent fir, growth = 50 percent of normal), no cutting or budworm attack.

No such mortality is applied to spruce, which continues to increase in volume, but more slowly as the area ages. Soon after year 70, the decline in fir exceeds gains in spruce, so growth on the entire 1,000-acre forest becomes negative. If the simulation were carried further, without harvesting or budworm attack, the entire fir area would be regenerated in year 120 when only percent of the original volume would remain.

Budworm Attack in Year 60, No Protection

In this example, normal growth proceeds as above for 60 years when a budworm attack begins. Survival rates were set at 60 percent for spruce and 20 percent for fir. Fir mortality begins 2 years after the onset of the outbreak; spruce begins to die 2 years later (4 years after the outbreak begins). During the 6-year mortality sequence that follows, growth is reduced to only 20 percent (for fir) and 50 percent (for spruce) of the preoutbreak rates.

The yield curves for both species decline sharply as mortality proceeds (Fig. 8). Mortality ends in years 68 and 70 for fir and spruce, respectively, growth reduction stops, and normal (preoutbreak) growth resumes. Three hundred acres of spruce (60 percent of the total) and 100 acres of fir (20 percent) survive the outbreak, and continue to advance in age. The old surviving age class is stocked at the same level per "model" acre as if no mortality had occurred, but occupies fewer acres. This causes the entire forest to be understocked.

During the outbreak, the remaining area—200 spruce and 400 fir acres—is "killed." All merchantable volume on this area is lost as tree mortality. These areas are regenerated, forming a new age class but remaining in the same species category. The simulated budworm mortality has, in effect, created a two-aged structure over the entire 1,000-acre forest, which originally consisted of only one age class.

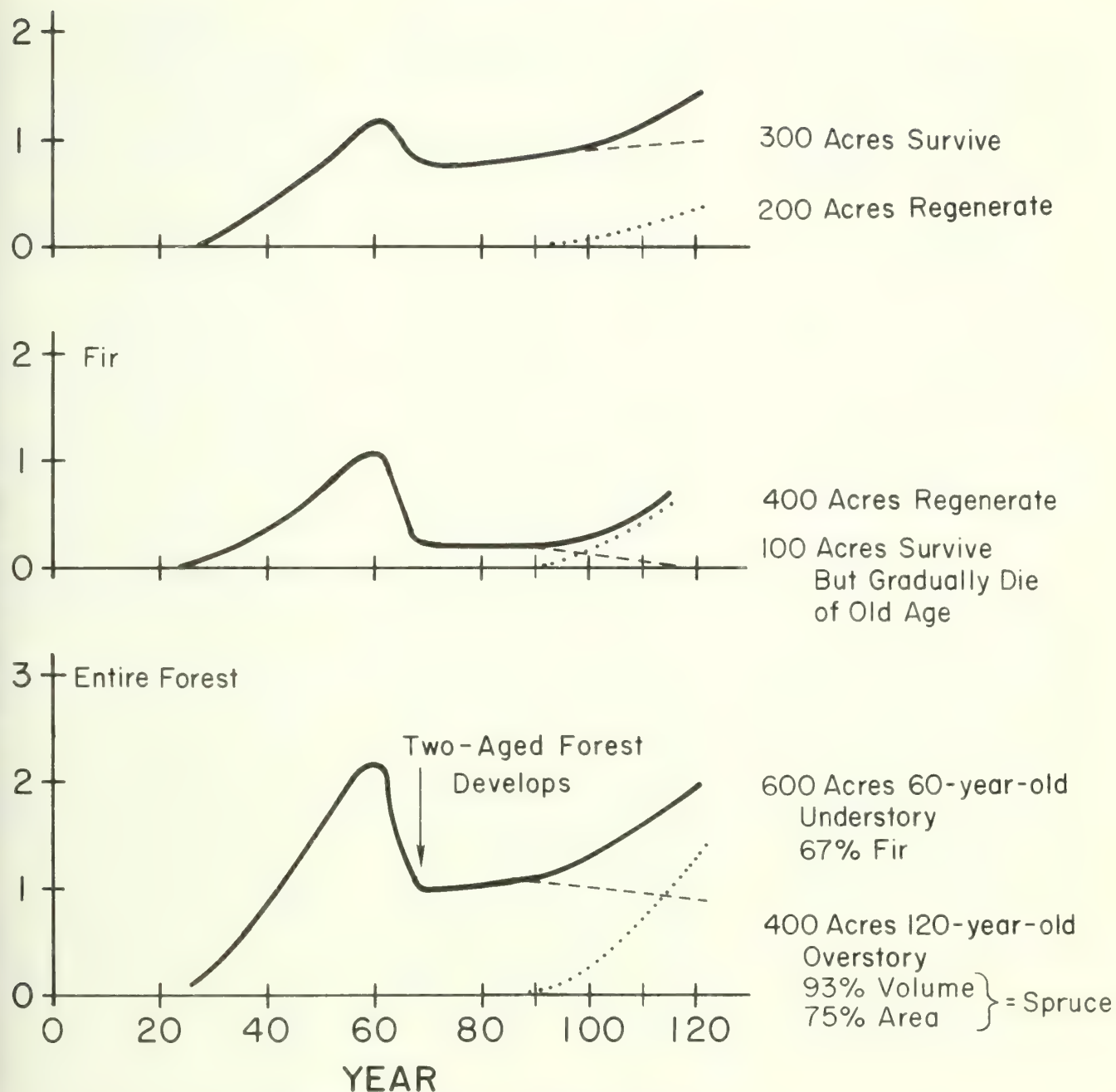


Figure 8.—Simulated growth and development of a hypothetical 1,000-acre spruce-fir forest (50 percent fir, growth = 50 percent of normal), attacked by budworm in year

In the postoutbreak forest, the surviving fir area continues to lose volume due to old-age mortality. On a forestwide basis, however, these losses are offset by growth of surviving spruce, which now makes up 75 percent (300 of 400 acres) of the old-age class. Surviving areas continue to gain volume until about year 90 when old-age fir mortality finally exceeds growth of spruce (Fig. 8, declining dashed line). However, growth on the entire forest remains positive, and even begins to accelerate as the new budworm-origin age class (dotted line) becomes merchantable. Sixty percent of the forest area—600 “model” acres—is now between 15 and 25 years old. This age class grows at the same per-acre rate as its predecessor did initially, though its species composition has changed in favor of fir.

At the end of the simulation, the total area of each species is the same as at the beginning, but the age and volume structures have changed significantly. Ninety-three percent of the volume and 75 percent of the area in the 120-year-old surviving age class is spruce, whereas two-thirds of both the volume and area in the budworm-origin age class, now age 60, is fir. If protection had been applied during the outbreak period, more area would have survived depending upon the strategy used, and less area would have been regenerated.

Harvest Half the Volume in Year 60

This example begins with the same initial conditions as the previous two cases. In year 60, a harvest of 1,068 million ft³—half the

standing volume—is made with a 10-percent discrimination against fir. Composition of the regeneration is set at 90 percent fir.

As described previously, the species composition of the harvest is determined by adding the user-specified discrimination level to the percentage of fir in the inventory. In this example, a 10-percent discrimination against fir is added to an inventory of 50 percent fir, which gives a harvest of 60 percent fir (641,000 ft³). The balance (427,000 ft³) is from spruce. At year 60, old-age fir mortality has not yet become important, so the per-acre stocking of both species is identical. Thus, areas harvested are directly proportional to the volumes removed. In this example, harvesting half the volume removes and regenerates half, or 500 acres, of the total forest, leaving an equal area in the old age class. Sixty percent (300 acres) of the harvest was fir; 200 fir and 300 spruce acres were left as a residual.

The residual areas follow the same development pattern observed in the two previous examples: slow increase in volume initially, then a decline as spruce growth slows and fir mortality increases with advancing time and age (Fig. 9). The major difference is in the regeneration response. Here, 90 percent of the area harvested (450 acres) regenerates to fir, leaving only 50 acres in young spruce. Overall forest composition changes from 50 to 65 percent fir as a result. This did not occur in the previous example (Fig. 8) because areas do not change species composition after budworm mortality.

Summary

Using the model to simulate more elaborate forest structures and management strategies is a straightforward extension of the processes illustrated. Forecasts could be done entirely by hand if it were not for the tremendous volume and repetitive nature of the calculations and bookkeeping. The algorithm was programed only to expedite these tedious procedures; it *does not* determine particular outcomes. The number of possible interactions among forest structure, natural processes, and management activities is virtually infinite. However, because the user specifies the rate and timing of each process, as well as the initial forest structure to which they are applied, all such effects are explicit. Within broad limits, the user essentially creates a unique model of his or her own special situation without being constrained by particular “built-in” assumptions that he or she may find unacceptable. Default procedures occasionally are needed to cover special cases.

It should be apparent from the examples cited that the model is not limited to forests composed entirely of even-aged stands. Any stand structure can be accommodated if the different age classes are separated when initializing the forest for simulation. New age classes are regenerated by the model whenever a disturbance removes some portion of the area from merchantable age classes, just as in nature. The 1,000-acre forest used in the examples is arbitrary. These simulations could just as easily be viewed as a 1-acre, even-aged “stand” which gradually develops a two-story structure after being attacked by budworm, harvested, or allowed to grow old and die naturally.

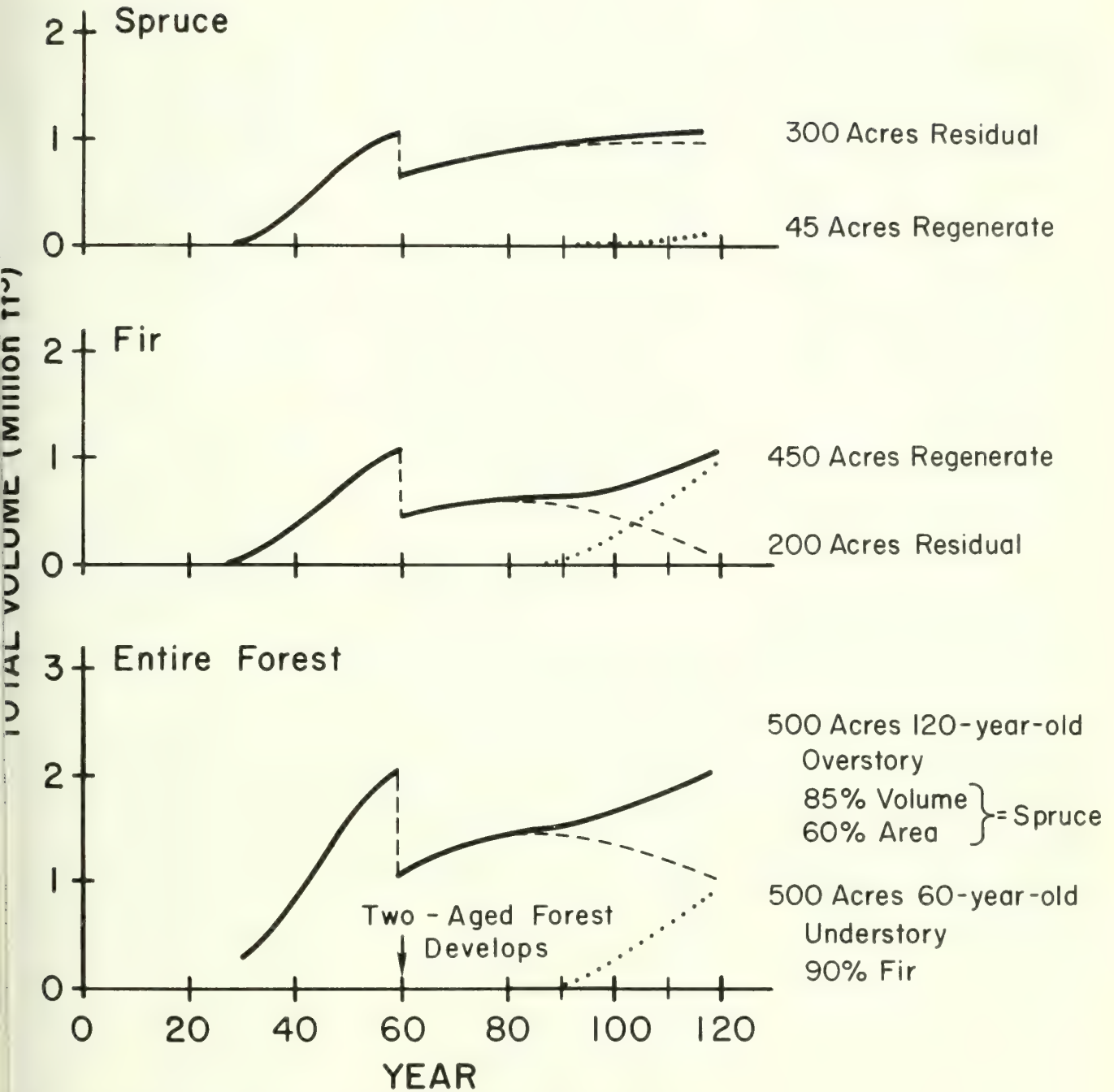


Figure 9.—Simulated growth and development of a hypothetical 1,000-acre spruce-fir forest (50 percent fir, growth = 50 percent of normal), with half of the total volume harvested in year 60 using a 10-percent discrimination against fir.

Wood Supply-Forest Protection Analysis

Misunderstandings sometimes can develop when age-class distributions are derived from traditional forest inventory plots. The basic problem is that the area represented by a single plot probably bears no relationship (except for perhaps a coincidental one) to the actual scale of the overstory-removal and regeneration processes in spruce-fir forests. Consider the case in which the basic sampling unit, for example a 1-acre plot, is occupied by trees in each of two 1/2-acre age classes. One originated after a commercial clearcut 80 years ago, and second started 20 years later after a tree-killing budworm outbreak. By conventional definitions, this plot, or the stand in which it is located, would not be considered even-aged because the majority of the stocking cannot be assigned to a single age class. Yet, as illustrated in Fig. 8, the model will accurately reproduce such a stand structure, and can accept such data as initial input. If the spatial distribution of the mortality, harvesting, and regeneration phenomena are ignored, the model accurately replicates the true forest dynamics.

In lieu of improved mensurational procedures, approximations can be used to derive an age structure from existing data. The key is to estimate the area occupied by each age class, if more than one is present. These areas are then separated in the model even though they are intermingled within the same stand. An example of how to deal with multiple age classes within stands is presented in the next section.

This section discusses how the model can be used to assist managers or policy analysts who are faced with problems connected with budworm-infested spruce-fir forests. Emphasis is on deriving model inputs from conventional forest inventory information that is commonly available to resource managers. We assume that potential users already have structured their problems for analysis and need only technical guidance in obtaining or adapting their own information.

The example is structured around a special interactive computer program (Appendix II), which facilitates creating and modifying the basic input data file. Input data are organized into seven main categories on a convenient summary form (Appendix III) that follows exactly the order of entry in the interactive program. Special worksheets (Appendix IV) have been prepared to aid in translating inventory data into the required model inputs.

Before specific technical details are discussed, a caveat on model use is necessary. The structure of this model allows an exceedingly diverse array of "what if" questions to be posed. This extreme flexibility can be a great asset under the proper circumstances, but can also be abused by careless, uncritical users. Analysts must exercise care to ensure that input data are as realistic as possible; the model will readily accept biologically impossible combinations of forest dynamics or artificial forest structures. Where information is poor and assumptions must be made, results must be interpreted with caution. When faced with uncertainty, users always should view the results in the following manner: "If the dynamic processes proceed as I have assumed, *then* the results are the best estimate of what I can expect the future to look like."

Available Information

This example illustrates how the model can be applied using a forest-type map and associated inventory data. Township 14 Range 6 in northern Maine near St. Pamphile, Quebec, was part of a demonstration area established by the Green Woods Project in cooperation with Seven Islands Land Co., which manages the town. Its history, current forest structure, and management problems are typical of a road region in Maine, and it illustrates how the model can be used to design harvesting and protection strategies to cope with the current budworm infestation.

In 1976, a forest-type map was prepared for the town by J. W. Sewall Co., Old Town, Maine. Stands were classified on black and white copies of color infrared aerial photography (1:15,840) according to forest type, height class, and density. The following categories were used:

Road forest type	Forest stand code		
	First	Second	Third ^a
S	Softwood code	Softwood code	Any code or "/"
SH	Softwood code	Hardwood code	Any code
HS	Hardwood code	Softwood code	Any code
H	Hardwood code	Hardwood code	Any code or "/"

^a The third species code, if present, represents an important component of the stand described by the first two codes.

Height (feet) Forest ground conditions

= 0-15	sw = Wet, swampy
= 15-30	ry = Rocky
= 30-50	sr = Steep and rocky
= 50 +	ll = Site II

History of stand

Forest closure	br = Burn
= 81-100	wf = Windfall
= 61-80	pc = Partial cut
= 31-60	pl = For logs
= 0-30	pp = For pulp
	cc = Clearcut
	di = Disease/insect
	of = Agricultural
	pn = Plantation

Where possible, individual species were distinguished, and the stand history, if known, recorded. Each stand was assigned a unique number and its area determined. All information was encoded in a computer file, with individual records for each stand.

During 1979 and 1981, 286 10-BAF prism plots were taken to determine volume per acre by species. Sample trees of each species were bored to determine age (total age or age since release). Milacre regeneration plots were taken to assess stocking on cutover areas. Plots were distributed among 25 separate strata to characterize each according to factors influencing forest growth and vulnerability to budworm damage.

Derivation of Input Data

Deriving model inputs is a straightforward process. The necessary steps are given below in the order required by the interactive program. A numerical code is used to link the text with the specific item on the input summary form (Appendix III).

Step 1

Specify the simulation parameters (Appendix III, 1.1 to 1.7). These variables control program execution and determine the types and frequency of output. The option used to stock and grow the forest depends on the nature of the data available to the user. In our example, the function option was selected for both purposes, though either could have been used to initialize the simulated forest.

Step 2

Divide the forest area into strata that are similar with respect to potential growth and development, budworm vulnerability, and application of forest protection and harvesting. On T14 R16, analysis revealed that the forest structure could be characterized effectively for simulation by combining the 25 sampling strata into three categories:

1. Mature, fully stocked stands with no history of cutting or major disturbance since 1950 (S3A, S3B, S4A, S4B stands).
2. Stands that had been partially cut since 1950 and had developed a two-story structure (typically S4C, SH4C stands).
3. Stands that had been clearcut since 1950, with essentially no merchantable trees remaining on the site and all growing space allocated to regeneration (S3D, S4D, SH3D, SH4D stands).

Step 3

Determine areas, merchantable cubic-foot volumes per acre for spruce and fir, and the age classes represented in each stratum (Worksheet 1). On T14 R16, the volume of fully stocked, mature softwood stands averaged 1,913 ft³/acre, 54 percent of which was fir. Merchantable trees ranged in age from 50 to more than 100 years from release.

A total of 988 acres of softwoods was recorded as having been partially cut since 1950, primarily by diameter-limit rules which varied by species. These stands have a two-story structure, with a residual overstory of old trees stocked at 1,242 ft³/acre and a new age class of advanced regeneration developing in openings created by the partial cuts. These two age classes must be separated in the model, ideally by measuring the actual areas occupied by trees in both age classes. In practice, this is difficult to determine directly, so an alternative approach is used. The volume of the overstory in this stratum averages only 65 percent (1,242/1,913) of the stands considered to be fully stocked. If it is assumed that the portion of the stand actually occupied by mature trees is stocked at the same level as the uncut fully stocked stands, this would give 65 percent of the area (641 acres) to the 60–100 age classes, leaving 35 percent (347 acres) to allocate to the regeneration in the 0–30 age classes.

Many of the softwood stands clearcut since 1950 fall into the S4D type, which contains virtually no overstory; most merchantable trees were cut in the logging operation, or have blown down since. This acreage was allocated entirely to the 0–30 age class with no volume per acre.

The corresponding strata in the mixedwood type were treated identically, and should be self-explanatory.

Step 4

Distribute the area in each forest type by 10-year age class. Enter the total stratum areas at the bottom of each column (the Total line) in Worksheet 2. For each stratum separately, determine the proportion of the total area that falls into each 10-year age class. If ages were assigned to plots in the field, this is simply the distribution of plots by age class in each stratum (weighted appropriately by the sampling scheme used). If no ages are available, one can simply specify percentages that seem to reflect the history of major stand-creating disturbances on the area. For example, records indicate that T14 R16 was heavily logged between 1870 and 1890 for old-growth spruce and pine, and then suffered severe mortality during the 1910–20 budworm out-

break. These correspond to the 91+ and 61–70 age classes, respectively, in 1980. Most of the area clearcut the last 30 years originated during the 1970's, and was allocated accordingly.

For each stratum, multiply the total area by these proportions to obtain areas by age class. Then for each forest type (softwood and mixedwood), add across all strata to obtain the total acreage in each age class. Divide these areas into the total type area (Appendix III, 2.1 and 2.2) for the overall age-class distribution (2.3 and 2.4) needed by the model. The resulting age-class distribution for the softwood type is given in the "percent" column under all strata on Worksheet 2 and is shown in Figure 10.

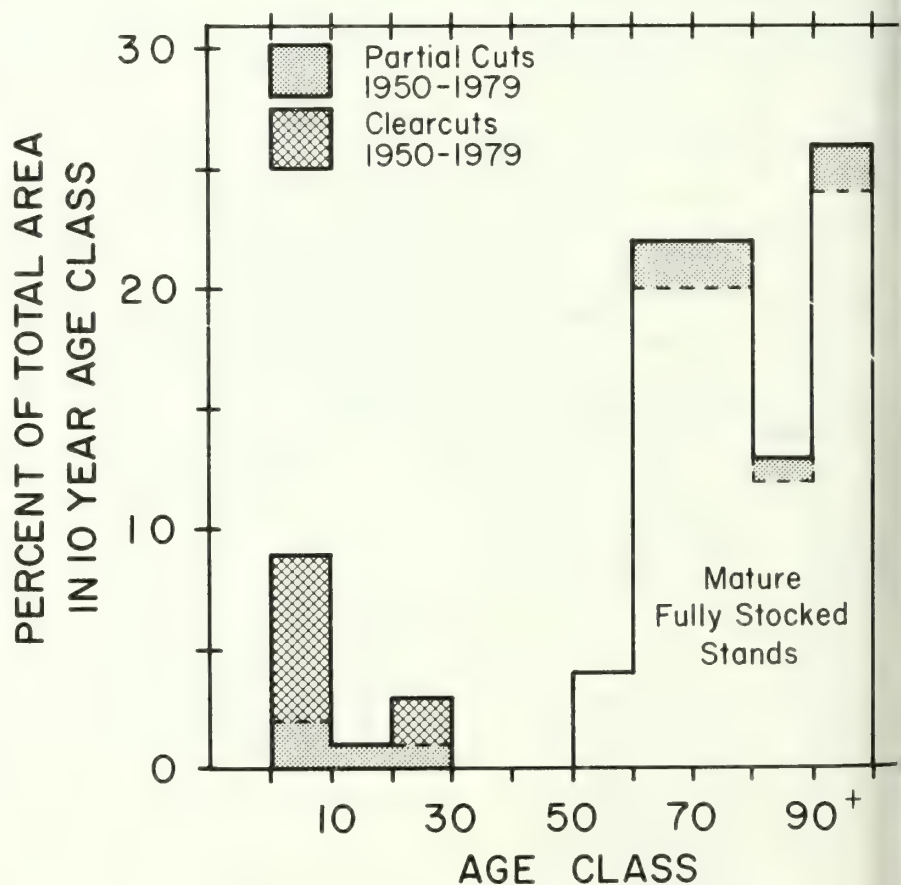


Figure 10.—Age structure of T14 R16.

At this stage, users can stock a forest with the percent-of-normal option or supply actual volumes per acre. This example illustrates the percent-of-normal option.

Step 5

Estimate percent stocking by age class. From the age structure (Appendix III, 2.3 and 2.4) derived in Step 4 (Worksheet 2), calculate a weighted average age for all classes that contain volume. Determine the volume per acre of a fully stocked

stand of the same age from Meyer's tables (Appendix I). Remember to use Site Index 50 for the softwood type (Appendix III, 2.10) and Site Index 60 for the mixedwood (2.11). Divide the normal stocking from Meyer's tables into the actual volume per acre of spruce and fir to obtain percent stocking for all merchantable age classes.

For example, the average age of merchantable softwood area on T14 R16 is nearly 80 (calculated from Worksheet 2). According to Meyer's tables, an 80-year-old "normally

stocked" stand has about 5,700 ft^3/acre . Actual stocking is only 1,913 cubic feet (Worksheet 1), or about 34 percent of normal. Stocking can be varied by age class to account for past understocking effects. As a first approximation, age classes over 80, which contain stands that were attacked by the budworm when young, were assumed to be less well stocked (30 percent) than 50- to 70-year-old stands (40 percent); the 71- to 80-age class was assumed to be in an intermediate position (Worksheet 2, Fig. 11).

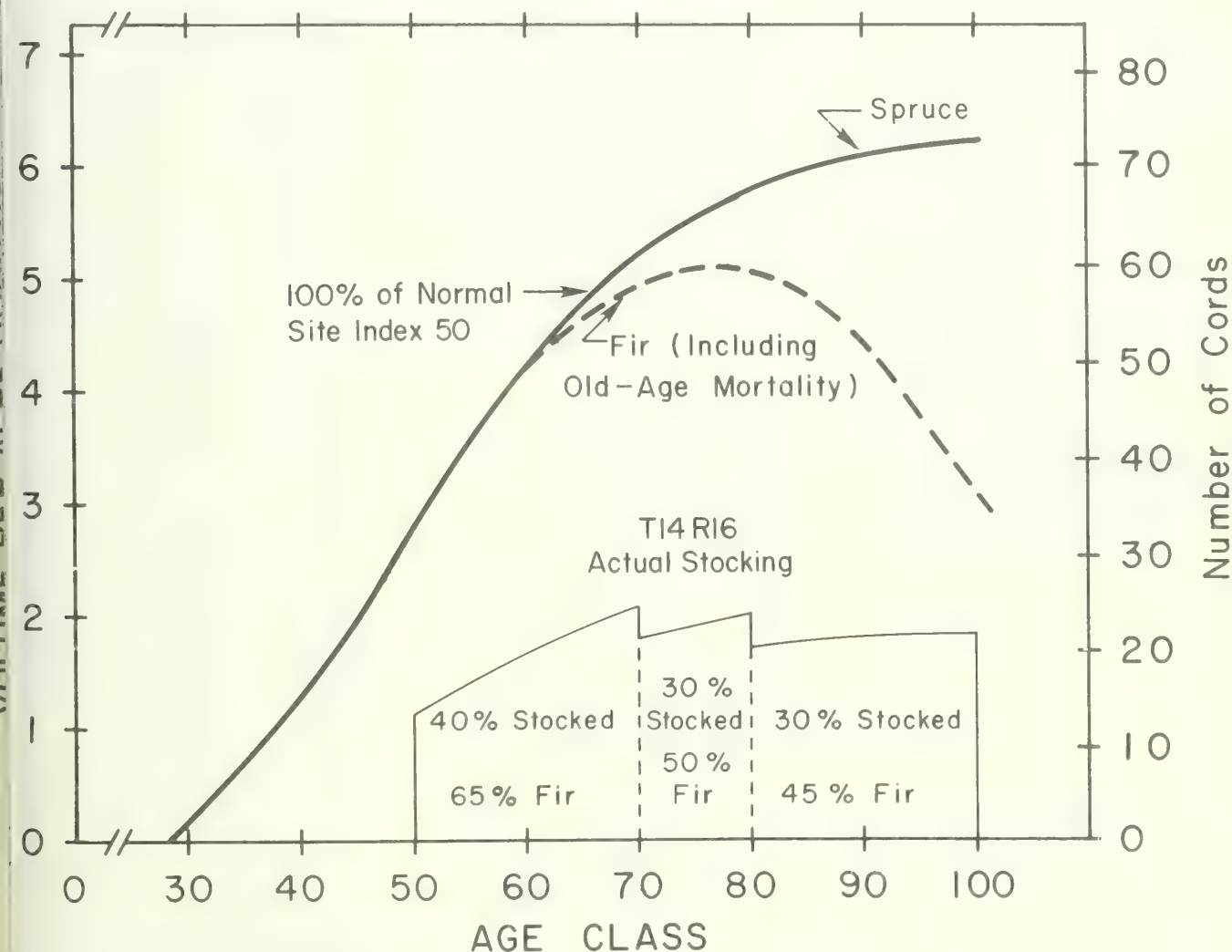


Figure 11.—Actual stocking of T14 R16 compared with Meyer's normal yield table.

Step 6

Calculate percent fir by age class (Appendix III, 2.12 and 2.13). For age classes with merchantable volume, the percentages should reflect the proportions of fir by volume in each. In the mature softwood stands, (including the residual areas from the older partial cuts), fir averaged about 52 percent of all merchantable volume in the softwood type on T14 R16 (Worksheet 1). One can assume that this percentage applies equally to all age classes, or change the percentages according to a knowledge of the area or more refined data. For example, one might assume that 51- to 70-year-old stands that originated after the last budworm outbreak have a higher proportion of fir than the older age classes which originated after logging. In this example we assumed that 65 percent of the young (51-70) areas were fir, compared with only 45 percent of the stands over 80 years old.

For age classes below 30, areas cannot be assigned in proportion to volume because no merchantable timber is present. Here, the appropriate figure is the percentage of the total volume that will be fir once the stands become merchantable at age 25. Normally, one would obtain these data from regeneration plots. However, the appropriate value is not necessarily the same as the measured percentage in newly established reproduction, since the proportions by species can change by age 30—either through natural development or deliberately from the application of early cultural practices.

Step 7

Specify the optimum rotation age that would be used if the forest were fully regulated (Appendix III, 2.14). As described in the section on timber harvesting, this parameter is used only to compute an index of how well regulated the forest is at any point during a simulation. It is not used to control simulated harvesting operations; these are governed as described in Step 12. In

this case, available markets are mainly for sawtimber, and the landowners would like to regulate their forest on about a 70-year rotation to ensure a steady supply of large-diameter material.

Step 8

Assign growth rates by species and forest type. If information from remeasured plots is available, the user should specify growth rates directly in cubic feet per acre by species and 20-year age class (Appendix III, 3.1 and 3.2). Unfortunately, no remeasured plots were available for T14 R16, so we chose to predict growth with equations fitted to Meyer's normal yield data (Appendix I) with appropriate adjustments for below normal stocking. In this example, the value chosen theoretically should correspond to the stocking of stands in the 51-70 age classes that have grown essentially undisturbed since 1920. In this case, 40 percent of normal (Site Index 50) was used for both spruce and fir in the softwood type (Appendix III, 3.3), and 30 percent of Site Index 60 for the mixedwood (3.4).

Step 9

Specify regeneration assumptions. On T14 R16, milacre plots showed a high proportion of fir in the softwood reproduction, and also some mixedwood cutover that was understocked with softwood species. On the basis of these data, we assumed that 30 percent (Appendix III, 4.5) of the mixedwood forest type will be converted to hardwood stands (lost from the spruce-fir resource), and that 10 percent (4.4) of the softwood cutovers would be mixedwood types when they reached merchantable size. Softwood regeneration was set at 80 percent fir (4.3), which means that 80 percent of the area and volume will be fir when the regenerated area becomes merchantable at age 25. Softwood cutovers generally were well stocked, so no lag (4.1a, 4.2a) period was specified. Eighty percent of the mixedwood cutovers (4.2b) were lagged by 15 years (4.1b)

to account for the greater abundance of competing species on these sites. No planting for type conversion from hardwood was planned (4.6).

Step 10

Determine mortality lag and budworm severity factors. The simulation was begun in 1979; the budworm outbreak began in the early 1970's. However, the simulated budworm outbreak cannot begin before the first year of the simulation, so we started the budworm outbreak in 1979 (Appendix III, 5.1) also. Mortality was just beginning that year on the lands that had been left unprotected since the early 1970s, so the difference is unimportant because we could specify a lag of zero years for fir (6.1b) and 2 years (6.1c) for spruce. This means mortality began immediately for fir and in 1981 for spruce on the unprotected lands.

It was assumed that virtually all of the fir over age 40 would be killed without protection, with slightly higher survival in the mixedwood type and in stands below age 40. For the 41-70 and 71+ age classes, expected fir survival was set at 5 percent (5.6 b-c) and 20 percent (5.6 b-c) of the total volume for the softwood and mixedwood types, respectively. For fir below age 40, expected survival was set at 40 (5.6a) and 70 percent (5.8a), respectively. For spruce over age 40, 60 (5.7 b-c) and 80 percent (5.9 b-c) of the volume was assumed to survive in the softwood and mixedwood types, respectively. Ninety percent of young spruce was assumed to survive in both types (5.7a and 5.9a).

Growth of unprotected fir and spruce was set at 20 (5.4a) and 50 percent (5.5a), respectively, of their normal rates without a budworm outbreak. Growth was reduced on protected lands to only 50 (5.2a) and 60 percent (5.3a) of the uninfested rates for fir and spruce. Growth reduction was applied for 20 years (until 1999), then eliminated on the premise that the budworm outbreak would end by then.

Formulating a Management Strategy

Step 11

Allocate forest protection (Worksheets 2-3). A major use of the model is determining the area that must be protected against budworm-caused tree mortality to meet forest management objectives. Before the model is used, it is necessary to determine the maximum area that physically can be protected with current spray technology. Then, simulation is used to arrive at the actual percentage of this zone that must be protected to sustain a given annual harvest.

The maximum feasible protection zone was developed for T14 R16 from the type map (for stand boundaries) and high-altitude color infrared aerial photography (to assess current tree condition). Blocks as small as 100 acres were drawn with irregular boundaries to include as many high-volume softwood and mixedwood stands as possible, while attempting to exclude other nontarget types. For each stratum, areas in and out of the protection zone were determined by adding the known acreages from the computer stand listings. Borderline stands (those including area both in and out of the protection zone) were planimetered and the areas allocated accordingly.

Of the total protection zone area of 6,037 acres, 512 acres were nonspruce-fir types, mostly "islands" of hardwood or cedar swamp that were impossible to include when drawing block boundaries (Worksheet 3). The remaining 5,525 acres were in one of six strata used to classify the forest structure for simulation. Thus, these acres (92 percent of the total area sprayed) make up the maximum possible area that can be protected in any simulation for this township.

To run the model, the user must specify the percentage of the 0-40, 41-70, 71+ age groups (by forest type and species) to protect (Worksheet 3, columns 5-6).

Because these limits do not necessarily coincide with those of the strata on Worksheet 1, the total protected area must be apportioned to age classes. In this example, we distributed the protected area within each stratum according to its overall age structure. In the fully stocked, mature softwood stands, 4,019 acres fell into the protection zone; this was allocated to age classes from 50 to 100 as shown in Worksheet 2. Similarly, 192 acres of old partial cuts were in the protection zone, which was allocated to the 0-30 and 41-100 age classes. Sixty-five acres of stands clearcut in 1950 also were included. The protected areas in each 10-year age class from each stratum were then added to produce the overall age structure of the protection zone by forest type. Protected areas were summed within the three age groups (Worksheet 2), and the percentage of the total land under protection calculated (Worksheet 3).

For example, the total area protected in the 0-40 stands is $34 + 13 + 85 = 132$ acres, which is 13 percent of the 1,024 softwood acres in these age classes.

These percentages can be applied equally to the spruce and fir areas within each age group, or varied to simulate a program targeted on one species. On T14 R16, some of the mature softwood area was excluded from the protection zone because stand composition was nearly pure spruce. These stands tend to be older hybrid red-black spruce, which usually does not require protection. Thus, the 2,913 acres under protection in this age group (Worksheet 3) probably have a higher proportion of fir than the total area. If the area under protection is 60 percent fir compared with the average of 45 percent for the total area (Worksheet 3), then the percentage of fir to protect in the 71+ age group is found by the formula

$$\frac{(\text{Total protected area}) (\% \text{ fir})}{(\text{Total area}) (\% \text{ fir})} = \frac{(2913) (.60)}{(4943) (.45)}$$

= .79 percent protected

Enter the derived protection percentages (Worksheet 3, columns 5-6) on the input summary form (Appendix III, 6.1, columns d-o).

Running a Simulation

Step 12

Formulate a harvesting strategy. If the simulation covers an historical period to aid in calibrating growth and mortality, harvest levels usually can be obtained from records. Virtually any strategy can be simulated, subject only to the potential limitations imposed by exhausting merchantable inventories. For the analysis of T14 R16, several elements were varied, including the total volume removed, percent fir in the harvest, and the proportion of the cut to be salvaged from dead material.

Initially, the harvesting parameters were set at a best estimate of the current strategy. The annual allowable cut had been 5,000 cords (425,000 ft³) (Appendix III, 7.1b), 70 percent of which was fir. As the inventory is only 52 percent fir, the discrimination against fir (from Figure 6 or calculated from the formula in Appendix I) is 0.18 (Appendix III, 7.1d). Markets limited the percentage of deadwood to 10 percent of the total cut (7.1h). Eighty percent of simulated harvests were concentrated on unprotected lands (7.1f) through 1985 to presalvage as much wood as possible before it was killed by the budworm. In 1986, (7.2a) 90 percent of the cut was allocated back to the protected lands (7.2f) to reduce protection requirements and avoid overcutting the unprotected lands, which become depleted through budworm mortality and presalvage operations. The salvage goal was reduced to 5 percent (7.2h).

Step 13

Use the interactive program to construct and format the basic data file, calibrate the initial forest structure, and run a simulation. After the input data have been assembled as described in Steps 1 through 12, the interactive program (Appendix II) is used to construct the formatted data file needed to execute the main program. The interactive program queries the user for each item, following the order of the input summary form (Appendix III). This requires no programming expertise, and should be self-explanatory.

When all data have been entered, the user usually runs the interactive program several times to "fine tune" the initial forest characteristics. Stocking levels and age-class data are changed heuristically until the inventory of the simulated forest agrees with the actual values. The interactive program is designed so that any selected input parameters can be changed quickly and efficiently without needless repetition. Inconsistencies in the original data may become apparent, and judgment is needed when changes must be made. With experience, users should be able to arrive at close agreement after only a few iterations.

Exploration of Scenarios

Once the initial forest structure is calibrated, further modifications to the input data file usually are limited to changes in management strategy. At this stage, typical uses would be to derive the minimum protection zone required to ensure a particular harvest level, or to determine the maximum sustainable harvest possible under a fixed level of protection.

It is important to recognize that, unlike certain harvest scheduling models which give "optimum" solutions, this model is not designed to give users "the answer" in one run. Each simulation is a unique result of the particular management strategy interacting with the specified forest dynamics, both of which are under the user's control. An adequate, thorough analysis requires many runs in which critical assumptions are varied to see if they affect the outcomes. Many sources of uncertainty merit serious scrutiny, including the accuracy of the user's conception of the initial forest structure; whether the key forest dynamics (growth, budworm damage, regeneration) develop as expected; and whether the simulated management intervention (harvesting, protection and silviculture) can be implemented as planned.

Through repeated simulations users begin to appreciate that a wide range of "futures" is possible. Since the future can never be rendered certain, the understanding of these complex and dynamic interactions gained in the analysis probably is more valuable to the manager than any single detail of the output.

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Appendix I

Meyer's Yield Table

Merchantable cubic-foot volume per acre of red spruce in and above the 4-inch diameter class; 1-foot stump allowance, 3-inch top inside bark.

Total age (years)	Site index				
	70	60	50	40	30
	----- (- ft ³ -) -----				
30	500	340	210	88	
40	2160	1650	1110	600	138
50	4780	3770	2760	1670	480
60	6850	5550	4200	2750	940
70	8100	6620	5150	3470	1400
80	8880	7280	5700	3920	1670
90	9300	7650	6000	4160	1800
100	9570	7870	6190	4310	1900
110	9800	8050	6350	4440	1990

Tabular values can be approximated by the Weibull distribution function:

$$(1) \text{ Volume} = K \{ 1 - \exp - [(A - c)/b]^a \}$$

where A = age

exp denotes exponentiation to the base e (2.71828); and other parameters are as follows:

Parameter	Site index				
	70	60	50	40	30
K	9561	7,867	6,250	4323	1964
a	1.81	1.83	1.85	1.89	2.12
b	31.8	31.85	33.4	32.6	37.8
c	24.4	25.0	25.0	27.6	29.0

Net growth is calculated from the derivative (Weibull density) of (1):

$$(2) \text{ Net growth} = K \{ (a/b) [(A - c)/b]^{a-1} \exp - [(A - c)/b]^a \}$$

Optional Old-Age Mortality Function for Balsam Fir

When the forest is initialized, a logistic function can be applied (at the user's option) to "understock" balsam fir area over age 50:

$$(3) \text{ MORT} = [1. + \exp(9.8148 - 0.09815 \times \text{AGE})]^{-1}$$

where exp denotes exponentiation to the base e (2.718..)

MORT = the proportion of the total volume lost to natural old-age mortality by a given AGE.

The function was formulated to give 5 percent mortality by age 70 and 95 percent cumulative mortality by age 130.

During a simulation, mortality is applied annually (at the user's option) using the derivative of this function:

$$(4) \text{ MORT} = [0.09815 \times \exp(A)] \times [1. + \exp(A)]^{-2}$$

where A = 9.8148 - 0.09815 × AGE, and

MORT = annual (unadjusted) mortality, expressed as a proportion of the original volume.

Before the mortality is applied, it is divided by the factor:

(1. - sum of all previous mortality rates)

to account for the fact that mortality is applied to the existing (not original) volume.

Species Discrimination Function for Simulated Harvesting

$$\%CUT = \%INV + [\%INV \times (1 - \%INV)]^x$$

$$\text{where } x = \text{Log}_e(\text{DISCRIM}) / -1.3863$$

DISCRIM = harvest discrimination parameter, defined as the difference between %CUT and %INV when %INV = 0.5 (i.e., the "extra" proportion of fir in the cut, above that in the inventory, when the inventory is 50:50 spruce-fir).

%CUT = proportion of fir in harvest (range = 0 - 1.0)

%INV = proportion of fir (by volume) in harvestable age classes

If harvest discrimination against *spruce* is specified, the "+" becomes a minus.

Three levels of editing are available, depending on the needs of the user and his familiarity with the model. The INITIAL format is for first-time users or for constructing an input data file from scratch. This option includes detailed prompts for information which should be virtually self-explanatory to any user with a general understanding of the model structure. The order of data input follows exactly the INPUT SUMMARY FORM (APPENDIX III); if the user can complete this form, he should have no trouble responding to the queries of the INITIAL format. The GENERAL format is designed primarily for inexperienced users, and omits much of the detailed descriptions which become repetitive for users at this level of understanding. The SPECIFIC format is designed to allow minor changes in the input data file (such as a simple change in one aspect of the harvesting strategy) to be made efficiently and without needless repetition of prompts.

All programs are presently operational at the University of Maine at Orono computing center, which uses IBM's Conversational Monitoring System (CMS). With little modification, the complete package could be installed on any IBM system that supports PLI, FORTRAN, WATFIV, SAS, and an EXEC facility. The model itself (without peripherals) can be run under any system that supports PLI and has sufficient memory. Programming expertise and experience with the operating system at the particular installation would be needed initially to make the package operational. At this stage, users probably would "customize" the package to produce the particular kind of output desired. Once the package is installed and the system linkages debugged, anyone who can use a terminal, with or without programming ability, should be able to carry out a simulation successfully.

Appendix II

Programming Considerations

Interactive Program for Constructing and Modifying Input Data Files

Potential users are often prevented from applying large simulation models because they lack programming expertise or are not conversant in the command language used to create and edit data files or run programs at their particular installation. To overcome these obstacles, an interactive program was developed that allows computer novices to use the model as readily as experts. The interactive program is essentially a customized editor which prompts the user in plain English for instructions or data inputs. Data are checked for errors and to see if they lie within acceptable ranges, and error messages are produced as appropriate. It also initiates simulations (executes the model) and produces tabular and graphical output of the results.

Software and Operating Systems

The main simulation program is written in PLI, and will compile under the IBM PLI/F compiler. The object deck requires at least 512K bytes of core to load and execute. Due to its large size, the program generally is run in batch mode. The interactive data entry program is written in WATFIV and is executed by an EXEC file.

Two auxiliary programs are also available to summarize simulation results in a more usable form. The first gives tabular listings of the output; it is written in FORTRAN and compiles under the IBM FORTG compiler. The second produces a graphical output and is written in the command language of the Statistical Analysis System (SAS).

Appendix III

Summary Form for Input Variables

1. SIMULATION PARAMETERS

- 1.1 TITLE: _____
- 1.2 SIMULATION PERIOD: from _____ to _____ LENGTH OF SIMULATION (YEARS): _____
- 1.3 PRINT ANNUAL REPORT? _____
- 1.4 PRINT AGE-CLASS INVENTORY TABLES EVERY _____ YEARS
- 1.5 PROCEDURE TO INITIALIZE FOREST: NORMAL YIELD FUNCTION _____ OR ACTUAL VOLUMES PER ACRE _____
- 1.6 PROCEDURE TO GROW FOREST: GROWTH FUNCTION _____ OR ACTUAL GROWTH RATES _____
- 1.7 APPLY OLD-AGE MORTALITY FUNCTION FOR FIR? _____

2. FOREST CHARACTERISTICS

FOREST LAND AREA

2.1 SOFTWOOD TYPE: _____ thousand acres

2.2 MIXEDWOOD TYPE: _____ thousand acres

AGE-CLASS DISTRIBUTION (% OF TOTAL AREA BY 10-YEAR AGE CLASSES)

	0-10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
2.3 SOFTWOOD	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
2.4 MIXEDWOOD	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____

IF USING NORMAL-STOCKING OPTION, SKIP TO 2.10

VOLUME PER ACRE (MERCHANTABLE CUBIC FEET) BY SPECIES, FOREST TYPE AND 10-YEAR AGE CLASS:

	0-10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
5 FIR, SW	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
6 SPRUCE, SW	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
7 FIR, MW	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
8 SPRUCE, MW	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____

PROPORTION FIR IN UNMERCHANTABLE (0-10, 11-20, 21-30) AGE CLASSES

	0-10	11-20	21-30
9	_____	_____	_____

SKIP TO 2.14

NORMAL STOCKING BY FOREST TYPE AND 10-YEAR AGE CLASS (PROPORTION OF YIELD FUNCTION):

	0-10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
10 SOFTWOOD	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
11 MIXEDWOOD	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____

PROPORTION FIR BY FOREST TYPE AND 10-YEAR AGE CLASS:

12 SOFTWOOD	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
13 SOFTWOOD	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____

14 OPTIMUM ROTATIION AGE: _____

3. FOREST GROWTH RATES

IF GROWTH FUNCTION OPTION WAS SPECIFIED, SKIP TO 3.3

NET GROWTH PER ACRE BY SPECIES AND 20-YEAR AGE CLASSES:

	25-30	31-50	51-70	71-90	91+
3.1 FIR	_____	_____	_____	_____	_____
3.2 SPRUCE	_____	_____	_____	_____	_____

PROPORTION OF FUNCTION-CALCULATED OR USER-SPECIFIED GROWTH TO APPLY BY SPECIES AND FOREST TYPE:

3.3 SOFTWOOD TYPE FIR: _____ SPRUCE: _____

3.4 MIXEDWOOD TYPE FIR: _____ SPRUCE: _____

4. FOREST REGENERATION RATES

4.1 REGENERATION LAG (YEARS) FOR SOFTWOOD (a) _____ MIXEDWOOD (b) _____

4.2 PROPORTION OF REGENERATED AREA LAGGED: SOFTWOOD (a) _____ MIXEDWOOD (b) _____

4.3 PROPORTION OF FIR IN SOFTWOOD REGENERATION _____

4.4 PROPORTION OF HARVESTED SOFTWOOD ACRES REGENERATING TO MIXEDWOOD _____

4.5 PROPORTION OF HARVESTED MIXEDWOOD ACRES REGENERATING TO HARDWOOD _____

4.6 ANNUAL AREA OF HARDWOOD ADDED TO SOFTWOOD SPRUCE _____ thousand acres

5. BUDWORM EFFECTS

1 YEAR TO BEGIN BUDWORM OUTBREAK: _____

2 GROWTH REDUCTION RATES BY SPECIES AND PROTECTION STATUS:

	GROWTH LOST	
	(% OF PRE-OUTBREAK)	DURATION (YEARS)
	(a)	(b)
2 PROTECTED FIR	_____	_____
3 PROTECTED SPRUCE	_____	_____
4 UNPROTECTED FIR	_____	_____
5 UNPROTECTED SPRUCE	_____	_____

6 SURVIVAL RATES (PROPORTION OF INITIAL VOLUME) IN UNPROTECTED AREAS, BY BROAD AGE CLASS:

	0-40	41-70	71-150
	(a)	(b)	(c)
SOFTWOOD FIR	_____	_____	_____
SOFTWOOD SPRUCE	_____	_____	_____
MIXEDWOOD FIR	_____	_____	_____
MIXEDWOOD SPRUCE	_____	_____	_____

6. FOREST PROTECTION STRATEGIES

PROPORTION OF AREA WHERE NO MORTALITY WILL OCCUR

BY FOREST TYPE, SPECIES, AND BROAD AGE CLASS:

		MORTALITY												
YEAR TO	LAG (YRS)		SOFTWOOD FIR			SOFTWOOD SPRUCE			MIXEDWOOD FIR			MIXEDWOOD S		
BEGIN	FIR	SPRUCE	0-40	41-70	71+	0-40	41-70	71+	0-40	41-70	71+	0-40	41-70	
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	
6.1	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	
6.2	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	
6.3	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	
6.4	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	
6.5	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	
6.6	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____	

7. HARVESTING STRATEGIES

0 YOUNGEST HARVESTABLE AGE, BY SPECIES: FIR _____ SPRUCE _____

		SPECIES		PROTECTED LAND			
		DISCRIMINATION		ALLOCATION		CUT FROM	DEAD WOOD IN
YEAR	HARVEST VOLUME (M FT ³)	CODE	%	CODE	%	OLDEST (%)	UNPROT. CUT (%)
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
1	_____	_____	_____	_____	_____	_____	_____
2	_____	_____	_____	_____	_____	_____	_____
3	_____	_____	_____	_____	_____	_____	_____
4	_____	_____	_____	_____	_____	_____	_____
5	_____	_____	_____	_____	_____	_____	_____
6	_____	_____	_____	_____	_____	_____	_____
7	_____	_____	_____	_____	_____	_____	_____
8	_____	_____	_____	_____	_____	_____	_____

NOTE: UP TO 30 HARVEST STRATEGIES CAN BE SPECIFIED SIMPLY BY REPEATING THESE ENTRIES.)

SPECIES DISCRIMINATION CODES:

0 = NO DISCRIMINATION

1 = DISCRIMINATION AGAINST FIR

2 = DISCRIMINATION AGAINST SPRUCE

PROTECTED LANDS ALLOCATION CODES:

0 = NO DISCRIMINATION (HARVEST BOTH LAND TYPES IN PROPORTION TO THEIR OCCURRENCE)

1 = CUT SPECIFIED PROPORTION FROM UNPROTECTED LANDS

2 = CUT SPECIFIED PROPORTION FROM PROTECTED LANDS

Appendix IV

WORKSHEET 1. SUMMARY OF FOREST INVENTORY INFORMATION NEEDED TO DERIVE MODEL INPUT DATA

STRATUM	AREA	RANGE IN AGE	VOLUME/ACRE (FT ³)				AVERAGE AGE	PERCENT OF NORMAL STOCKING
			FIR	SPRUCE	TOTAL	% FIR		
1 <i>Fully stocked mature softwood</i>	<i>6329</i>	<i>50-100</i>	<i>1030</i>	<i>883</i>	<i>1913</i>	<i>54</i>	<i>80</i>	<i>1913/5700 =</i>
2 <i>Softwood stands partially cut since 1950</i>	<i>988-347 641</i>	<i>0-30 regen. 60-100 overstory</i>	<i>476</i>	<i>766</i>	<i>1242 (65%)</i>	<i>38</i>		
3 <i>Softwood stands clearcut since 1950</i>	<i>677</i>	<i>0-30</i>	<i>0</i>	<i>0</i>	<i>0</i>	<i>regen. data 80</i>	<i>-</i>	<i>N/A</i>
4								
TOTAL, SOFTWOOD TYPE <i>7993</i>								
1 <i>Fully stocked, mature mixedwood</i>	<i>1942</i>	<i>50-100</i>	<i>1172</i>	<i>599</i>	<i>1771</i>	<i>66</i>	<i>80</i>	<i>1771/7280 =</i>
2 <i>Mixedwood partially cut since 1950</i>	<i>721-324 397</i>	<i>0-30 regen. 40-100 overstory</i>	<i>764</i>	<i>213</i>	<i>977 (55%)</i>	<i>78</i>		
3 <i>Mixedwood clearcut since 1950</i>	<i>591</i>	<i>0-30</i>	<i>0</i>	<i>0</i>	<i>0</i>	<i>regen 80</i>	<i>-</i>	<i>N/A</i>
4								
TOTAL, MIXEDWOOD TYPE <i>3254</i>								
TOTAL, ENTIRE FOREST <i>11,247</i>								

SHEET 2. DERIVATION OF TOTAL AND PROTECTED AREAS, PERCENT FIR, AND PERCENT STOCKING, BY 10-YEAR AGE CLASS

T: <u>T14 R16</u>			FOREST TYPE: <u>SOFTWOOD</u>									
STRATUM <u>1</u> <u>mature, fully</u> <u>stocked</u>			STRATUM <u>2</u> <u>recent</u> <u>partial cuts</u>			STRATUM <u>3</u> <u>recent clearcuts</u>			STRATUM TOTALS <u>ALL STRATA</u>			
TOTAL	PROT.		TOTAL	PROT.		TOTAL	PROT.		TOTAL	PROT.		
%	AREA	AREA	%	AREA	AREA	%	AREA	AREA	%	AREA	AREA	% FIR
10			<u>50</u>	<u>174</u>	<u>34</u>	<u>85</u>	<u>574</u>	<u>0</u>	<u>09</u>	<u>749</u>	<u>34</u>	<u>80</u>
20			<u>20</u>	<u>69</u>	<u>13</u>	<u>0</u>	<u>0</u>	<u>0</u>	<u>01</u>	<u>69</u>	<u>13</u>	<u>80</u>
30			<u>30</u>	<u>104</u>	<u>20</u>	<u>15</u>	<u>102</u>	<u>65</u>	<u>03</u>	<u>206</u>	<u>85</u>	<u>80</u>
40			<u>subtotal</u>	<u>347</u>					<u>-</u>	<u>0</u>	<u>-</u>	<u>-</u>
50									<u>-</u>	<u>0</u>	<u>-</u>	<u>-</u>
60	<u>05</u>	<u>316</u>	<u>201</u>						<u>04</u>	<u>316</u>	<u>201</u>	<u>65</u>
70	<u>25</u>	<u>1582</u>	<u>1005</u>	<u>20</u>	<u>128</u>	<u>25</u>			<u>22</u>	<u>1710</u>	<u>1030</u>	<u>65</u>
80	<u>25</u>	<u>1582</u>	<u>1005</u>	<u>30</u>	<u>192</u>	<u>37</u>			<u>22</u>	<u>1774</u>	<u>1042</u>	<u>50</u>
90	<u>15</u>	<u>949</u>	<u>603</u>	<u>20</u>	<u>129</u>	<u>25</u>			<u>13</u>	<u>1078</u>	<u>628</u>	<u>45</u>
00	<u>30</u>	<u>1899</u>	<u>1206</u>	<u>30</u>	<u>192</u>	<u>37</u>			<u>26</u>	<u>2091</u>	<u>1243</u>	<u>45</u>
			<u>subtotal</u>	<u>641</u>								
100	<u>6,329</u>	<u>4,019</u>	100	<u>988</u>	<u>192</u>	100	<u>677</u>	<u>65</u>	100	<u>7993</u>	<u>4276</u>	

WORKSHEET 3. DERIVATION OF TARGETED PROTECTION STRATEGY BY FOREST TYPE, AGE CLASS AND SPECIES

FOREST: T14 R16

FOREST TYPE AND AGE CLASS	TOTAL AREA		PROTECTED AREA		PERCENT PROTECTED	
	ACRES (1)	% FIR (2)	ACRES (3)	% FIR (4)	FIR (5)	SPRUCE (6)
SOFTWOOD						
0 - 40	<u>1024</u>	<u>80</u>	<u>132</u>	<u>80</u>	<u>13</u>	<u>13</u>
41 - 70	<u>2026</u>	<u>65</u>	<u>1231</u>	<u>65</u>	<u>61</u>	<u>61</u>
71+	<u>4943</u>	<u>45</u>	<u>2913</u>	<u>60</u>	<u>79</u>	<u>43</u>
TOTAL	<u>7993</u>		<u>4276</u>			
MIXEDWOOD						
0 - 40	<u>915</u>	<u>80</u>	<u>46</u>	<u>80</u>	<u>05</u>	<u>05</u>
41 - 70	<u>625</u>	<u>70</u>	<u>30</u>	<u>70</u>	<u>49</u>	<u>49</u>
71+	<u>1714</u>	<u>70</u>	<u>896</u>	<u>70</u>	<u>52</u>	<u>52</u>
TOTAL	<u>3254</u>					
TOTAL, SPRUCE-FIR RESOURCE	<u>11,247</u>		<u>5525</u>			
TOTAL, ENTIRE FOREST	<u>14,500</u>		<u>6037</u>			

(1), (2) and (3) are derived by adding areas in ten-year age classes from WORKSHEET 2.

(4) is specified to give desired level of targeted protection.

$$(5) = \frac{(3) \times (4)}{(1) \times (2)} \quad (6) = \frac{(3) \times [1.0 - (4)]}{(1) \times [1.0 - (2)]}$$

Seymour, Robert S.; Mott, D. Gordon; Kleinschmidt, Steven M.; Triandafillou, Peter; Keane, Robert. **Green Woods Model: a forecasting tool for planning timber harvesting and protection of spruce-fir forests attacked by the spruce budworm.** Gen. Tech. Rep. NE-91. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1985. 38 p.

A dynamic model of budworm-infested spruce-fir forests is described. The Green Woods Model allows managers and analysts to predict forest composition and structure that result from various harvesting and protection strategies. The forest structure is represented as a distribution of area and volume by age class, species, and forest type. This structure changes through time as the natural process of forest development (growth, budworm-caused growth loss and tree mortality, and regeneration) interact with management strategies (timber harvesting and protection). The model is inherently flexible; the rate and timing of virtually all modeled processes, both natural and management-related, are controlled by the user.

ODC U518.5:453 [*Abies balsamea* + *Picea*]: 145.7 x 18.28

Choristoneura funiferana

Keywords: simulation; wood-supply analysis; forest dynamics;
Choristoneura fumiferana; *Picea*; *Abies balsamea*.

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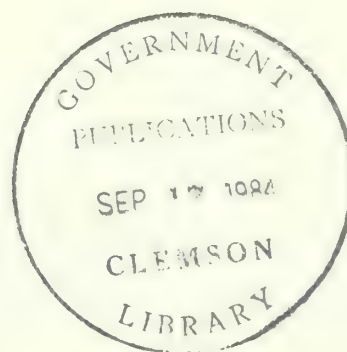
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A Program for Evaluating the Economic Effectiveness of Spruce Budworm Control with a Programmable Hand-held Calculator



The Author

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Abstract

Uncontrolled spruce budworm infestations can cause substantial losses of spruce-fir. With this program, a hand calculator can compute the net present worth and composite rates of return of control investments, before and after taxes. A worked-out example is given. If input-output forms are prepared in advance, as suggested, the calculator can be used without a printer in the field to generate on-the-spot estimates.

Note:

The computer program described in this publication is available on request with the understanding that the U.S. Department of Agriculture cannot assure its accuracy, completeness, reliability, or suitability for any other purpose than that reported. The recipient may not assert any proprietary rights thereto nor represent it to anyone as other than a Government-produced computer program.

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Program for Evaluating the Economic Effectiveness of Spruce Budworm Control with a Programmable Hand-held Calculator

Robert Marty

What this Program Does

Purpose. This program estimates the economic effectiveness of spruce budworm control, in individual stands or control blocks, by comparing the value of timber saved with control costs. It is designed to help forest managers and pest control specialists to identify those parts of an ownership where control benefits outweigh control costs.

The program described here was developed for use on a TI-59 pocket calculator, but can be used with appropriate modifications on any comparable programmable calculator. Program cards are available from the author, Robert Marty, Greentree Consultants, Inc., P.O. Box 27125, Lansing MI 48909, or from Daniel Schmitt, Northeastern Forest Experiment Station, 370 Reed Rd., Broomall, PA 19008.

Applicability. This program can be applied appropriately in the following circumstances:

- when an objective of management is commercial timber production
- when defoliation by spruce budworm has occurred for 2 or more consecutive years
- when harvest is not possible during the next 2 to 5 years because the stand is below merchantable size, or because markets are poor
- when an approved method of control exists and its application is feasible.

This program may be used both for public and private ownerships.

Inputs required. The following estimates are needed as program input:

- the number of years until the stand will be harvested
- full-stocking harvest volume
- the proportion of stand area occupied by fir
- the proportion of stand area occupied by spruce
- the proportion of fir volume which will be lost without control
- the proportion of spruce volume which will be lost without control
- the acceptable or guiding rate of return on control investments
- the anticipated stumpage price for fir
- the anticipated stumpage price for spruce
- the proportion of income accruing to the owner after taxes
- the proportion of cost incurred by the owner after taxes

- the number of years to each anticipated treatment
- the cost of each anticipated treatment

Outputs provided. The program outputs the following estimates:

- fir harvest volume without control
- spruce harvest volume without control
- fir harvest volume saved by control
- spruce harvest volume saved by control
- the discounted value of treatment costs
- the value of volume saved at harvest
- the discounted value of volume saved
- the net present value of control
- the rate of return to control
- the break-even percentage.

An Illustration of Analysis

Stand data inputs. Consider the following situation. Budworm control is under consideration for a stand where 52 percent of the stand area is occupied by fir and 8 percent by spruce. The stand is scheduled for harvest in 15 years when spruce-fir yield on fully stocked acres will be 46 cords. If budworm is not controlled we anticipate a loss of 75 percent of fir harvest volume, and 10 percent of spruce harvest volume.

Volume estimates. The program calculates that without budworm control, harvest volumes will average 6.0 cords per acre of fir and 3.3 cords per acre of spruce. Control will save an additional 15.2 cords of fir and 0.3 cords of spruce per acre.

Economic data inputs. Four percent has been selected as the minimum real rate of return (rate above the inflation rate) acceptable for control actions. We anticipate that the real price of pulpwood stumpage will increase modestly during the next 15 years to \$7 per cord for fir and \$10 per cord for spruce. Since this is a public ownership there are no reductions in costs or incomes due to tax effects. We expect that a control treatment will be necessary immediately, and then at 2-year intervals, on the average, until harvest. Treatment now costs about \$5 per acre, and is not expected to increase in real terms.

Cost, value and profit estimates. The program calculates that the discounted value of the eight control treatments is \$30.89 per acre, that the value at harvest of the volume saved by control will be \$109.87 per acre, and that the discounted value of that income is \$61.01. From these estimates the program further calculates that the net present value of control is \$30.12 per acre, that the

BUDWORM CONTROL

rate of return to control is 8.8 percent, and that the control investment would still earn the minimum acceptable rate of 4 percent if stumpage prices were 51 percent of those expected. Figure 1 shows the printer output for this program, and Table 1 contains a glossary of printer output symbols.

Table 1.—Glossary of printer output symbols.

YRS —	The number of years until harvest
MAX —	The spruce-fir yield per fully stocked acre of harvest, in cords
%F —	The proportion of stand area occupied by fir, percent
%S —	The proportion of stand area occupied by spruce, percent
-%F —	The proportion of fir harvest volume which will be lost without control, percent
-%S —	The proportion of spruce harvest volume which will be lost without control, percent
INT —	The minimum acceptable or guiding rate of return to control, percent
P/F —	The price of fir stumpage expected at harvest, dollars/cord
P/S —	The price of spruce stumpage expected at harvest, dollars/cord
ATI% —	The proportion of income that accrues to an owner after tax effects, percent
AIC% —	The proportion of cost that is borne by an owner after tax effects, percent
YEAR —	The number of years until a treatment occurs
COST —	The cost of treatment per acre protected, dollars
ΣPVC —	The sum of the present or discounted values of each treatment, dollars/acre
ATI —	The amount of after-tax harvest income added by control, dollars/acre
PVI —	The present or discounted value of ATI, dollars/acre
NPV —	The net present value of control = PVI - ΣPVC, dollars/acre
CRR —	The rate of return earned by the control investment, percent
BEP —	The break-even percentage

15.	YRS
46.	MAX
52.	%F
8.	%S
75.	-%F
10.	-%S
6.0	FIR
3.3	SPR
15.2	+F
0.3	+S
4.	INT
7.00	P/F
10.00	P/S
100.	ATI%
100.	ATC%
0.	YEAR
5.00	COST
2.	YEAR
5.00	COST
4.	YEAR
5.00	COST
6.	YEAR
5.00	COST
8.	YEAR
5.00	COST
10.	YEAR
5.00	COST
12.	YEAR
5.00	COST
14.	YEAR
5.00	COST
30.89	ΣPVC
109.87	ATI
61.01	PVI
30.12	NPV
8.8	CRR
0.51	BEP

Figure 1.—Printer output for the illustrative analysis.

How to Run this Program

The sequence of steps. The "Input-output guide" (Fig. 2) shows the exact sequence of steps necessary to carry out an analysis. The user first enters the program into program memory and initializes the program. The stand data are entered, volume estimates are outputted, economic data are inputted, and cost, value and profit measures are outputted. The "input" column on the guide has boxes for recording input data, and it shows the keys that must be pressed to enter each input and obtain each output. The guide, with blank boxes, is reproduced on the back cover. Make a copy of it when you want to do an analysis.

Program detail. This section tells you exactly what the calculator is doing each time you input data or output results. It provides the formulas used to calculate outputs from input data, gives guidance in developing inputs, and provides interpretations of outputs.

Doing an analysis. Make a copy of the Input-Output Guide and enter the values for inputs in the appropriate boxes. Follow the guide in entering inputs and outputting results. Record results in the appropriate boxes in the "output" column if you are not using a printer.

Program Detail

Program location

<u>keys pressed</u> ^{1/}	<u>Explanation</u>	<u>Display</u> ^{1/}
-----------------------------------	--------------------	------------------------------

-----STEP 0. ENTER AND INITIALIZE PROGRAM-----

2, 2nd OP, 17 Partitions memory as required by this program into 800 program locations and 20 data registers.

1	Read program card, side 1	1.
2	Read program card, side 2	2.
3	Read program card, side 3	3.

A program card side has been entered when its number appears in the display. If a flashing zero appears instead, clear it by pressing CE and re-enter the side. After the program is entered do the illustrative problem and make sure you can reproduce the indicated output values. This helps to assure you that the program is entered correctly in memory.

000	A	Resets program pointer to 000, prints title, clears data registers and display.	0
-----	---	---	---

^{1/} Data, input and display values are from the illustrative analysis just given.

INPUT-OUTPUT GUIDE

<u>Input</u>	<u>Explanation</u>	<u>Output</u>
-----STEP 0. ENTER AND INITIALIZE PROGRAM-----		
2, 2nd OP,17	Partitions memory as required	
	Read cards, three sides	
A	Starts program and prints title	
-----STEP 1. INPUT STAND DATA-----		
(15)	R/S Years to harvest	
(46)	R/S Full-stocking harvest volume, cds/acre	
(52)	R/S Area occupied by fir, percent	
(8)	R/S Area occupied by spruce, percent	
(75)	R/S Fir volume loss, percent	
(10)	R/S Spruce volume loss, percent	
-----STEP 2. OUTPUT VOLUME ESTIMATES-----		
B	Fir volume without control, cds/acre	(6.0)
R/S	Spruce volume without control, cds/acre	(3.3)
R/S	Fir volume saved by control, cds/acre	(15.2)
R/S	Spruce volume saved by control, cds/acre	(0.3)
-----STEP 3. INPUT ECONOMIC DATA-----		
(4)	C Guiding rate of return, percent	
(7.00)	R/S Fir stumpage price, \$/cd	
(10.00)	R/S Spruce stumpage price, \$/cd	
(100)	R/S After-tax income percent	
(100)	R/S After tax cost percent	
(0)	R/S Years to first treatment	
(5.00)	R/S First treatment cost, \$/acre	
	Repeat year and cost inputs for other treatments	
-----STEP 4. OUTPUT COST, VALUE AND PROFIT ESTIMATES-----		
E	Discounted value of treatment costs, \$/acre	(30.89)
R/S	Value of volume saved at harvest, \$/acre	(109.87)
R/S	Discounted value of volume saved, \$/acre	(61.01)
R/S	Net present value of control, \$/acre	(30.12)
R/S	Rate of return to control, percent	(8.3)
R/S	Break-even percentage	(0.51)

Figure 2.—Spruce budworm control economics program

Program location

Keys pressed

Explanation

Display

-----STEP 1. INPUT STAND DATA-----

15, R/S Enters into display, stores, 15.
and prints the number of
years until harvest.

46,R/S Enters into display, stores, 46.
and prints full stocking
volume at harvest, in
cords per acre.

Literature cited lists four sources of yield
information for spruce-fir: Meyer's (1929) normal yield
tables for red spruce, white spruce, and balsam fir in the
Northeast; Westveld's (1953) empirical yield tables for
spruce-fir in the Northeast; Gevorkiantz and Olsen's
(1960) yield tables for upland balsam fir in the Lake
Superior region; and Bowman's (1944) spruce-fir yield tables for
northern Michigan. Use these sources to estimate full
stocking volume at harvest if you do not have an
indicator of your own that you prefer.

52,R/S Enters into display, stores 0.52
and prints the proportion
of stand area occupied by
balsam fir, in percent.
Entered as a whole number
and stored as a decimal
fraction.

8, R/S Enters into display, stores 0.08
and prints the proportion
of stand area occupied
by spruce, in percent.
Entered as a whole number
and stored as a decimal
fraction.

Most spruce-fir stands are not fully occupied by
spruce and fir, but will have openings and areas occupied
by other vegetation. For example, forest survey data for
Wisconsin (Essex and Hahn 1976) show that only 54
percent of the volume on survey plots typed as spruce-fir
was of those species. Hemlock, pine, and larch may also
be defoliated by the spruce budworm. If any of these
species is being defoliated, include its stand area with the
spruce.

126 75, R/S Enters into display, stores 0.75
and prints the proportion of
balsam fir harvest volume
which it is anticipated will
be lost without budworm
control, due both to growth
loss and unsalvaged mortality,
in percent. Entered as a whole
number and stored as a decimal
fraction.

150 10, R/S Enters into display, stores 0.10
and prints the proportion of
the harvest volume for spruce
and other susceptible species
which it is anticipated will
be lost without budworm
control, in percent. Entered
as a whole number and stored
as a decimal fraction.

Estimates of losses due to budworm infestation are
uncertain. Some of the available information on loss is
presented in the Appendix, to help you make a judgement
about what level of loss to anticipate. It is appropriate to
repeat your analysis using several different loss
estimates.

<u>Program location</u> <u>keys pressed</u>	<u>Explanation</u>	<u>Display</u>
-----STEP 2. OUTPUT VOLUME ESTIMATES-----		
175 B	Calculates, prints and displays the volume of balsam fir at harvest without control, in cords per acre.	5.980

This estimate is calculated according to the following formula:

$$\text{FIR} = \text{MAX}(\%F) \cdot 1 - (-\%) \quad (\text{see Table 1})$$

For the illustrative example the calculation becomes:

$$\text{FIR} = 46(.52)(1 - .75) = 5.98 \text{ cords/acre.}$$

211 R/S	Calculates, prints and displays the volume of spruce at harvest without control, in cords per acre. Calculated as above.	3.312
245 R/S	Calculates, prints and displays the volume of balsam fir that will be added to harvest volume if budworm control is undertaken, in cords per acre.	15.249

This estimate is calculated according to the following formula:

$$+F = 0.85(\text{MAX})(\%F)(-\%F)$$

For the illustrative example the calculation becomes:

$$+F = 0.85(46)(.52)(.75) = 15.249 \text{ cords/acre.}$$

279 R/S	Calculates, prints and displays the volume of spruce that will be added to harvest volume if budworm control is undertaken, in cords per acre. Calculated as above.	0.3128
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Harvest volume estimates in this program assume clearcutting at harvest and are stated in terms of cords per acre. Conversion factors given in the Appendix may be used to convert cords to other measures of output where appropriate. This program should not be used where partial or selection harvests are planned.

The calculations for the volume that can be saved by control assume that 85 percent of the volume which will be lost to budworm infestation can be saved by control. If control experience in the situation under analysis differs substantially from this, reprogram program locations 258-9 and 292-3.

<u>Program location</u> <u>keys pressed</u>	<u>Explanation</u>
-----STEP 3. INPUT ECONOMIC DATA-----	
314 4,C	Enters into display, prints and stores the guiding, or minimum acceptable rate of return to control investments. The guiding rate is entered as a whole number and stored as one plus the interest rate expressed as a decimal fraction.

The guiding rate of return should be selected carefully to reflect the best alternate use of investment funds. The rate of interest may be a nominal rate or a real rate. A nominal rate of return includes the anticipated inflation rate, while the real rate does not. Thus, if the minimum acceptable rate of return to control investments is 4 percent above the inflation rate, and an 8-percent inflation rate is anticipated, then the real guiding rate is 4 percent and the nominal guiding rate is given by: $1.04(1.08) = 1.1232$ or 12.32%. It is usually simpler to use a real guiding rate and to express costs and incomes in constant dollars. If a nominal rate is used, inflated (or deflated) costs and prices must be used as well.

343 7, R/S	Enters in display, prints and stores the fir stumpage price anticipated at harvest, in dollars per cord.
-----------------	--

10, R/S Enters in display, prints and stores the spruce stumpage price anticipated at harvest, in dollars per cord. 10.

The prices entered above should reflect the mix of products anticipated and, in the case of spruce price, the weighted average price of all susceptible species included. For example, if half of the spruce harvest will be white pine wood selling for \$10 per cord, and the other half will be spruce sold as sawtimber at \$80 per Mbf, then converting the spruce timber value to a cord basis at 450 bd. ft. per cord would be \$36.00 per cord for the sawtimber portion, and an average price per cord of $\$10.00 + \$36.00 / 2$ or \$23.00 per cord.

100, R/S Enters into display, prints and stores the proportion of a revenue which is retained by the owner after income tax effects, in percent. Entered as a whole number and stored as a decimal fraction. 1.

100, R/S Enters into display, prints and stores the proportion of an expenditure which remains after income tax effects, in percent. Entered as a whole number and stored as a decimal fraction. 1.

Enter 100 percent for both revenues and expenditures when the stand being analyzed is in public ownership. If the stand is privately owned, then the appropriate percentages must be ascertained from the owner, since different owners are in different tax circumstances.

0, R/S Enters into display, prints and stores the number of years until the first control treatment will be applied to the stand. 0.

5, R/S Enters into display, prints and stores the before-tax cost per acre protected of the first treatment, in dollars per acre. Computes the discounted value of the after-tax cost. 5.

Repeat the year and cost entries for each expected treatment. Use zero for the year of first treatment when that treatment is expected in less than 1 year. If control is applied to an area larger than the stand area, compute cost per acre by dividing the total cost of the treatment by the number of acres in the stand. In this way both costs and benefits will be expressed as an average number of dollars per acre contained in the stand. Discounted values of costs are calculated by the formula:

$$PVC = \text{Cost} (ATC\%) / (1 + INT)^{\text{Year}}$$

In the illustrative analysis the discounted value of the second year cost is:

$$PVC = 5(1.0) / (1.04)^2 = \$4.62.$$

The present values of the after-tax treatment costs are summed in a data register as they are computed.

<u>Program location</u>		<u>Explanation</u>	<u>Display</u>
<u>keys pressed</u>			
<hr/>			
STEP 4. OUTPUT COST, VALUE AND PROFIT ESTIMATES <hr/>			
502	E	Prints and displays the sum of the discounted values of all treatments, in dollars per acre.	30.89...
525	R/S	Calculates, prints and displays the after-tax value at harvest of volume saved by control, in dollars per acre.	109.871

This calculation is made using the following formula:

$$ATI = ATI\% (+F)(P/F) + (+S)(P/S)$$

In the illustrative analysis this calculation is:

$$ATI = 1.00 (15.249)(7.00) + (0.3128)(10.00) = \$109.87$$

5, R/S Enters into display, prints and stores the before-tax cost per acre protected of the first treatment, in dollars per acre. Computes the discounted value of the after-tax cost. 5. 572 R/S Calculates, prints and displays the discounted value of harvest volume savings, in dollars per acre. 69.00...

The discounted or present value of after-tax harvest income saved by control is given by:

$$PVI = ATI/(1+INT)^{Years}$$

For the illustrative analysis the present value of income becomes:

$$PVI = 109.87/(1.04)^{15} = \$61.01$$

604	R/S	Calculates, prints and displays the net present value of control, in dollars per acre.	30.11...
-----	-----	--	----------

Net present value is defined as:

$$NPV = PVI - PVC$$

For the illustrative analysis NPV is given by:

$$NPV = 61.01 - 30.89 = \$30.12$$

When net present value is positive it indicates that the control opportunity earns more than the guiding rate of return and thus is acceptable from the financial point of view.

631	R/S	Calculates, prints and displays the rate of return to control, in percent per year.	8.82...
-----	-----	---	---------

Rate of return is calculated according to the following formula:

$$CRR = YRS \quad ATI/ \quad PVC \quad -1$$

In the illustrative analysis CRR is given by:

$$CRR = 15 \quad 109.87/30.89 \quad -1 = 8.8\%$$

This rate of return is the composite rate of return and is consistent with the net present worth measure of effectiveness. CRR indicates the average rate of return to the investment in control and can be compared directly with the guiding rate. Any control opportunity with a CRR larger than the guiding rate will also have a positive NPV. CRR can be used to rank control opportunities.

671	R/S	Calculates, prints and displays the present value of costs as a percentage of the present value of income, called the break-even percent.	0.506...
-----	-----	---	----------

Break-even percent is given by the following formula:

$$BEP = PVC/PVI$$

In the illustrative analysis BEP becomes:

$$BEP = 30.89/61.01 = 0.51$$

The BEP in this case indicates that even if income from control are only half of those expected, or even twice those expected, or any equivalent combination of the two, the control investment will still earn the guiding rate. BEP is a measure of the safety margin against an unacceptable outcome.

700	Program ends.
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DATA REGISTERS

00. Full stocking volume at harvest—cords per acre
01. Percent area occupied by fir—stored as a decimal fraction
02. Percent area occupied by spruce and other susceptible species—stored as a decimal fraction
03. Percent of fir harvest volume that will be lost to budworm—stored as a decimal fraction
04. Percent of harvest volume of spruce and other susceptible species that will be lost to budworm—stored as a decimal fraction
05. Fir volume saved by control—cords per acre
06. The volume of spruce and other susceptible species saved by control—cords per acre
07. The guiding rate of interest—stored as $(1+i)$
08. Time to harvest—years
09. Price of fir stumpage at harvest—dollars per cord
10. Weighted average price of spruce and other susceptible species at harvest—dollars per cord
11. After-tax income as a proportion of before-tax income—stored as a decimal fraction
12. After-tax cost as a proportion of before-tax cost—stored as a decimal fraction
13. Time until treatment j—years
14. Cost of treatment j—dollars per acre protected before taxes
15. Present value of treatment j—dollars per acre protected, after taxes.
16. Sum of the present values of all treatments—dollars per acre protected, after taxes
17. After-tax additional income at harvest due to control—dollars per acre
18. Present value of added income—dollars per acre
19. Intermediate calculations

Cited

Harold O.; Hastings, Arthur R. **How to rate vulnerability to budworm in Minnesota.** Unnumbered. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station; 1980. 4 p.

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Antz, S. R.; Olsen, Lucille P. **Growth and yield of red balsam fir in the Lake States.** Stn. Pap. 22. St. Paul, MN: U.S. Department of Agriculture, Forest Service, Lake States Forest Experiment Station; 1950.

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Appendix

Estimates of Volume Loss

Volume loss estimates are uncertain at best. The data presented in Tables 2 and 3 indicate the degree of mortality that can be expected as the result of an uncontrolled spruce budworm infestation which continues for 5 or more years. The location, frequency and severity of budworm infestation currently is not predictable. There have been 10 major spruce budworm infestations since 1904, giving an average frequency of one infestation every 25 or 30 years in some part of the range of the spruce-fir type in eastern North America.

Table 2. Mortality related to spruce budworm—Eastern Canada

Stand age (years)	Fir and spruce stocking (percent of total)	Percent of basal area killed	
		Fir	Spruce
60 or more	80 or more	98	
			31
	Less than 80	76	
Less than 60		59	16

Source: MacLean (1980).

Table 3. Mortality related to spruce budworm—Minnesota. In percent of fir basal area killed

Basal area of other species (percent)	Balsam fir basal area (ft ² per acre)					
	20	40	60	80	100	120
0	75	88	90	91	93	93
10	55	75	83	86	89	90
20	35	65	77	81	84	87
30	15	55	68	76	80	83
40		45	62	71	76	79
50		35	55	65	72	76
60		22	48	60	68	72

Source: Batzer and Hastings (1980).

Table 4. Product conversion factors: Equivalents of 1 cord of wood plus bark

Dbh ^{a/}	Cubic feet of solid wood	Total cubic feet of stumpage	International Rule board feet
4"	77	167	—
6"	84	130	250
8"	87	107	450
10"	90	107	550
12"	92	107	600

Source: Bowman (1944).

^{a/} Dbh class of tree of average basal area for all trees 3.5 inches dbh and larger.

Marty, Robert. **A program for evaluating the economic effectiveness of spruce budworm control with a programable hand-held calculator.** Gen. Tech. Rep. NE-92. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1984. 10 p.

Uncontrolled spruce budworm infestations can cause substantial losses of spruce-fir. With this program, a hand calculator can compute the net present worth and composite rates of return of control investments, before and after taxes. A worked-out example is given. If input-output forms are prepared in advance, as suggested, the calculator can be used without a printer in the field to generate on-the-spot estimates.

ODC 651.1

Keywords: Insecticide cost; computer programs;
economic analysis

INPUT-OUTPUT GUIDE

<u>Input</u>	<u>Explanation</u>	<u>Output</u>
-----STEP 0. ENTER AND INITIALIZE PROGRAM-----		
2, 2nd OP,17	Partitions memory as required	
	Read cards, three sides	
A	Starts program and prints title	
-----STEP 1. INPUT STAND DATA-----		
<input type="text"/>	R/S Years to harvest	
<input type="text"/>	R/S Full-stocking harvest volume, cds/acre	
<input type="text"/>	R/S Area occupied by fir, percent	
<input type="text"/>	R/S Area occupied by spruce, percent	
<input type="text"/>	R/S Fir volume loss, percent	
<input type="text"/>	R/S Spruce volume loss, percent	
-----STEP 2. OUTPUT VOLUME ESTIMATES-----		
B	Fir volume without control, cds/acre	<input type="text"/>
R/S	Spruce volume without control, cds/acre	<input type="text"/>
R/S	Fir volume saved by control, cds/acre	<input type="text"/>
R/S	Spruce volume saved by control, cds/acre	<input type="text"/>
-----STEP 3. INPUT ECONOMIC DATA-----		
<input type="text"/>	C Guiding rate of return, percent	
<input type="text"/>	R/S Fir stumpage price, \$/cd	
<input type="text"/>	R/S Spruce stumpage price, \$/cd	
<input type="text"/>	R/S After-tax income percent	
<input type="text"/>	R/S After tax cost percent	
<input type="text"/>	R/S Years to first treatment	
<input type="text"/>	R/S First treatment cost, \$/acre	
Repeat year and cost inputs for other treatments		
-----STEP 4. OUTPUT COST, VALUE AND PROFIT ESTIMATES-----		
E	Discounted value of treatment costs, \$/acre	<input type="text"/>
R/S	Value of volume saved at harvest, \$/acre	<input type="text"/>
R/S	Discounted value of volume saved, \$/acre	<input type="text"/>
R/S	Net present value of control, \$/acre	<input type="text"/>
R/S	Rate of return to control, percent	<input type="text"/>
R/S	Break-even percentage	<input type="text"/>

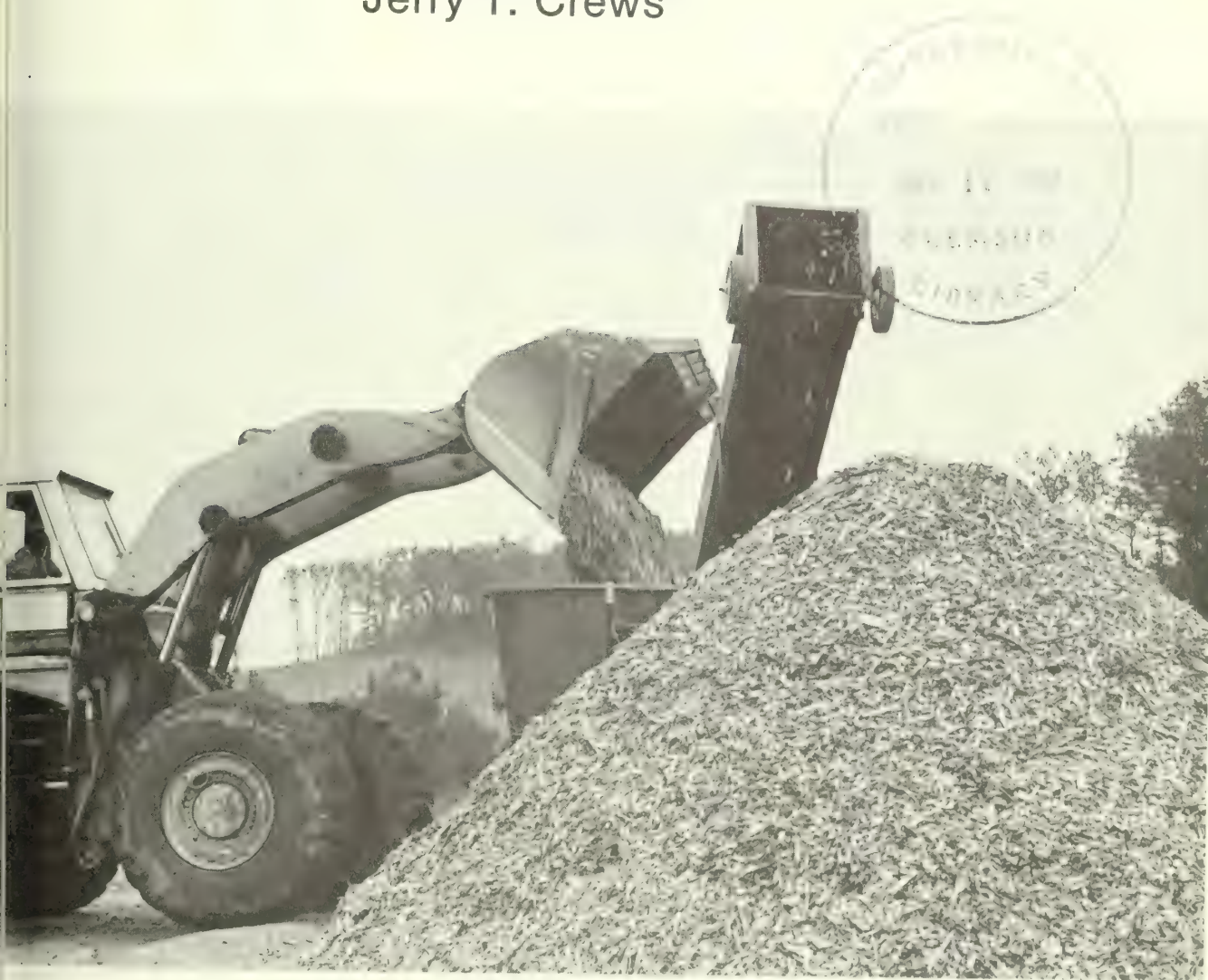
Headquarters of the Northeastern Forest Experiment Station are in Broomall, Pa. Field laboratories are maintained at:

- Amherst, Massachusetts, in cooperation with the University of Massachusetts.
 - Berea, Kentucky, in cooperation with Berea College.
 - Burlington, Vermont, in cooperation with the University of Vermont.
 - Delaware, Ohio.
 - Durham, New Hampshire, in cooperation with the University of New Hampshire.
 - Hamden, Connecticut, in cooperation with Yale University.
 - Morgantown, West Virginia, in cooperation with West Virginia University, Morgantown.
 - Orono, Maine, in cooperation with the University of Maine, Orono.
 - Parsons, West Virginia.
 - Princeton, West Virginia.
 - Syracuse, New York, in cooperation with the State University of New York College of Environmental Sciences and Forestry at Syracuse University, Syracuse.
 - University Park, Pennsylvania, in cooperation with the Pennsylvania State University.
 - Warren, Pennsylvania.
-



Response of Vegetation to Various Mulches Used in Surface Mine Reclamation in Alabama and Kentucky— 7-Year Case History

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The Authors

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Abstract

Five different mulches and one mulch-amendment combination were evaluated in the reclamation of two different mine spoils, one in western Kentucky and one in northern Alabama. The treatments evaluated were bark, hardwood chips, straw, hay, hydromulch, and hydromulch plus Petroset SB emulsion. Test plots, approximately 1 acre, were instrumented with flumes to monitor discharge, erosion transects to measure erosion, suction lysimeters for sampling groundwater, and devices to sample the runoff water. In the first years of the study, bark, hay, and straw generally produced the best vegetative cover. Mulches high in biomass tended to favor the establishment of legumes over grass. After 7 years, the effects of the different mulch treatments were readily apparent at the Alabama site where the hardwood-chip plot had strikingly superior cover. Differences were not so apparent at the Kentucky site.

Acknowledgments

This study would not have been possible without the cooperation and support of the coal companies that made land available for the study sites and loaned heavy equipment and operators to smooth the plots and form the berms, and in one instance supplied the fertilizer. Cooperators at the Fabius Mine in northern Alabama were Robertson and Associates and the Tennessee Valley Authority. The cooperator in western Kentucky was the Amax Coal Company at the Ayrgerm Mine.

roduction

About 200 thousand acres in the United States are disturbed by surface mining each year. All of this disturbed land is at least temporarily devoid of vegetation and exposed to erosion. Miners are now required to reclaim and revegetate the land they have disturbed. Mulches and/or chemical stabilizers or adhesives are frequently applied to the spoil surface to help reduce erosion and to speed the revegetation process. Mulches and soil stabilizers generally are considered useful in spoil reclamation; however, the true value and long-term effects on different spoils under different conditions of slope, aspect, and climate have not been investigated extensively. In this study we evaluated the long-term effects of six mulches (bark, wood chips, straw, hay, hydromulch, and petroset plus hydromulch) on growth of selected grasses and legumes and runoff and erosion from approximately 1-acre plots on two highly different types of spoils.

Experimental Design

In the spring of 1976, two research sites were established: the Fabius site in northern Alabama and the Ayrgem site in western Kentucky (Fig. 1). The spoil at the Ayrgem site was a gravelly sandy loam to sandy loam and at the Fabius site was a gravelly borderline sandy loam to loam. At each site seven mulch treatments, each approximately 1 acre, were delineated. Table 1 gives the treatment, slope, length, LS factor, and aspect. Berms were constructed to separate the plots and to direct runoff water into flumes instrumented with continuous discharge recorders and automatic water-sampling devices. Four suction lysimeters were installed on each plot so water for chemical analysis could be extracted periodically from the spoil at a depth of about 24 inches. Fifteen erosion basins, 48 inches across, of the type described by Curtis and Cole (1962) were installed on each plot in rows of three with each row offset so that no gully would cross more than one transect.



Figure 1.—Map showing site locations.

Table 1.—Plot treatment, slope, length, LS factor, and aspect

Treatment ^a	Slope	Length of plots	LS ^b factor	Aspect ^c
	Percent	Feet		Degrees
AYRGEM				
Petroset	12.8	400	4.00	48
Chips	12.6	400	3.90	48
Straw	12.3	400	3.76	48
Control	11.7	405	3.49	49
Hydromulch	12.3	415	3.83	47
Bark	11.4	410	3.38	46
Hay	12.3	390	3.71	46
FABIUS				
Petroset	13.2	322	3.77	326
Chips	13.2	290	3.58	328
Straw	16.7	278	5.14	332
Control	17.6	286	5.69	335
Hydromulch	15.8	296	4.84	337
Bark	10.7	306	2.65	339
Hay	14.6	266	4.03	318

^aPlot sequence is from left to right when viewed looking uphill.

^bComputed product of slope (L) and gradient (S) from Wischmeier and Smith (1965, p. 9) using the equation $LS = \sqrt{\lambda} (0.0076 + 0.0053s + 0.0076s^2)$ wherein λ is the field slope length in feet, and s is the gradient expressed as slope percent. The LS factors presented here indicate the computed ratio of plot erodibility to that of a "standard" plot 72.6 feet long with a 9% slope.

^cAspect is viewed looking downslope from top of plots to the bottom.

Each site was limed and fertilized in accordance with standard practices for reclamation at that mine. Lime was applied to the Ayrgem site in the winter of 1975-76 at the rate of 25 tons per acre. No lime was applied at the Fabius site.

The Ayrgem site was fertilized on April 14, 1976, at the rate of 400 pounds per acre diammonium phosphate (18-46-0), 100 pounds per acre muriate of potash (0-0-60), and 100 pounds per acre ammonium nitrate (33.5-0-0), then disked the same day. The Fabius site was fertilized on April 6, 1976, with 500 pounds per acre ammonium nitrate (33.5-0-0) and 500 pounds per acre superphosphate (0-18-0).

The Fabius site was seeded on April 6, 1976, to the following seed mix: 20 pounds per acre Ky-31 fescue (*Festuca arundinaceae*, selection Ky-31), 5 pounds per acre Kobe lespedeza (*Lepedeza striata* var. Kobe), 5 pounds per acre Korean lespedeza (*L. stipulaceae*), 5 pounds per acre sericea lespedeza (*L. cuneata*), and 1 pound per acre weeping lovegrass (*Eragrostis curvula*). The Ayrgem site was seeded on April 14, 1976, to the same mix except that 1 pound per acre Bermuda grass (*Cynodon dactylon*) was substituted for the weeping lovegrass. We thought that the Bermuda grass would perform better on the extremely sandy spoil.

The seven mulch treatments at each site were applied within 4 days of seeding, except for the bark and wood-chip mulches that were applied 23 days after seeding at the Ayrgem site. Mulches were applied at the

following rates: (1) Petroset SB emulsion¹ at 40 gallons per acre plus hydromulch² at 500 pounds per acre, (2) hardwood chips at 40 to 50 cubic yards per acre, (3) straw at 3,000 pounds per acre, (4) control, (5) hydromulch at 1,500 pounds per acre, (6) bark at 40 to 50 cubic yards per acre, and (7) hay (predominantly grass) at 3,000 to 3,500 pounds per acre. An asphalt emulsion tackifier was used to hold the straw and hay in place at the Fabius site.

Tackifier was not used at the Ayrgem site, and much of the hay and straw was blown off within a few days after application. Thus, on May 18-20, 1976, hay and straw were reapplied to these plots at the rates of 3,000 and 2,000 pounds per acre, respectively.

Vegetative cover was evaluated near the end of each growing season from 1976 through 1979 by measurement of a line intercept along the perimeters of 15 different foot-square transects on each plot. The intercepts of vegetation (including crown, stem, and individual leaves) were measured at precisely the same spot each time, uphill and to the right of the left post

of each erosion transect. Legume and grass intercepts and overlap of grass and legume species along the transects were evaluated separately. Total cover was computed by adding the grass and legume intercepts and subtracting the overlap.

Toward the end of the 1979 and 1980 growing seasons, 20 foot-square sections of vegetation were selected at random on each plot at Ayrgem and harvested. Similar samples were collected in 1979 at Fabius. Near the end of the 1982 growing season, 15 similar vegetative samples were harvested from each plot at Ayrgem and Fabius. The vegetation rooted in each square was clipped about a half inch above the ground, separated into grass and legume components (except for 1979 Ayrgem harvest), air dried, weighed, and the yield computed.

Three sets of spoil samples (0 to 6 inches deep) were collected and analyzed during the course of this study. The first set of 8 to 10 samples per plot was collected in March and April 1976, the second set (7 to 10 samples per plot) in August 1977, and the third set at various dates from October 1982 to March 1983. This third set was composed of nine samples per plot and analyzed as three composite samples (top, middle, and bottom)

The coarse fragment percentage, particle-size distribution, spoil texture, and moisture retention characteristics were all determined on spoils collected in the third sampling (1982-83). Spoil not passing through a 2-mm dry sieve after light grinding in a mortar and pestle was reported as

¹Petroset SB emulsion is a soil binding petrochemical product of the Phillips Petroleum Corporation. The use of trade, firm, or corporation names in this paper is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture or the Forest Service of any product or service to the exclusion of others that may be suitable.

²Hydromulch is a wood-fiber product composed largely of cellulose.

large fragments. Particle-size distribution was determined using the hydrometer procedure of Patrick (1958) and the USDA diameter designations: sand 0.05 to 2 mm, silt 0.002 to 0.075 mm, and clay less than 0.002 mm. Soil moisture retention was determined on the less than 2-mm fraction at 1/3 and 15 bars pressure by pressure plate apparatus.

The following determinations were made on the less than 2-mm soil fraction. Spoil pH values and specific conductances were determined from 1:2 spoil to water extracts (dry basis). Sulfates were analyzed as 1:10 spoil to water extracts, and the observed concentrations multiplied by 10 to convert back to an air-dry basis. Total exchange acidity and exchangeable aluminum were obtained using the procedure of Yuan (1959), except that aluminum was determined on the extracts using a Perkin-Elmer atomic absorption spectrophotometer (model 2380 for the 1976-77 samples and model 503 for the 1976-77 samples).

Response of Vegetation to Mulches

Vegetative cover on each plot at the end of the first four growing seasons is illustrated in Figure 2. Vegetation yields for the fourth, fifth, and seventh growing seasons are given in Table 2. Appreciable differences are attributable to mulches, yet responses to each mulch follow different patterns on the two sites because of the differences in aspect, climate, and spoils. Possibly, too, the hay, straw, hardwood chips, and bark used in Alabama could have differed enough from the corresponding mulches used in Kentucky to have had a measurable effect on vegetative growth. Because of the different responses observed at the two sites, it seems necessary to discuss the responses separately for each site.

Ayrgem Site

First Season. Total live vegetative cover was most complete (59 percent) on the bark plot, followed by 40 percent live cover on the hay plot.

The Petroset (30 percent), hydromulch (29 percent), straw (22 percent), and chip (19 percent) plots did not differ greatly from the control (23 percent). Growth of legumes was very sparse on the petroset plot (8 percent of the live vegetative cover), hydromulch plot (12 percent), and control plot (12 percent); yet, legumes formed the bulk of the live vegetative cover on the remaining plots: chips (66 percent), bark (62 percent), hay (60 percent), and straw (57 percent).

Second season. Live vegetative cover increased on all except the Petroset plot during this second season even though no Bermuda grass had survived the winter. Bark mulch with 81 percent total live cover was still the best, and hay mulch with 55 percent live cover was still second best. Straw and chips each had 48 percent live cover, and hydromulch had 40 percent. The Petroset (25 percent) and control (23 percent) plots had the least live cover. Legumes were the predominant vegetation on all plots.

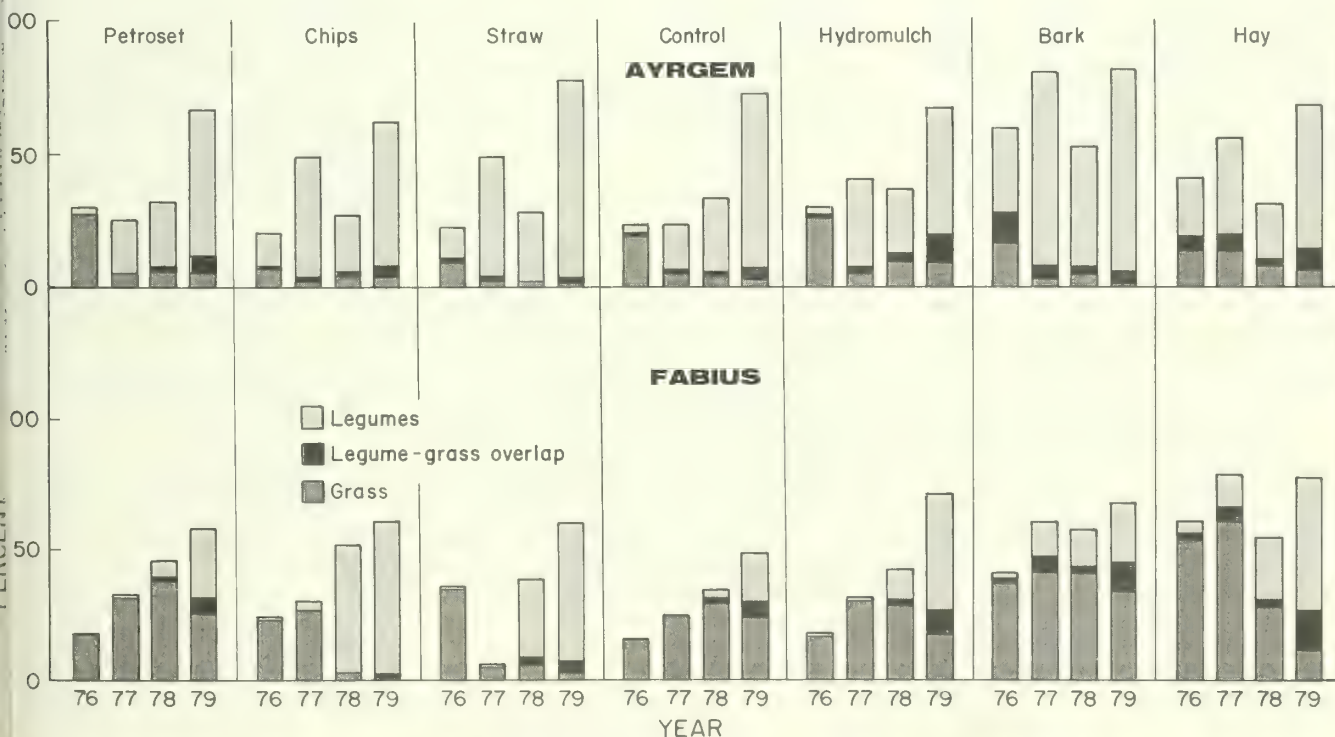


Figure 2.—Percentage of late-season vegetative cover and proportion of grasses and legumes at the Ayrgem and Fabius sites, 1976-79.

Table 2.—Vegetative yields from the Ayrgem and Fabius sites, 1979, 1980, and 1982, in pounds per acre (dry matter)

Treatment	Grass + Legumes			Grass			Legumes		
	1979	1980	1982	1979	1980	1982	1979	1980	1982
AYRGEM									
Petroset	4,810	5,080	12,970	—	220	540	—	4,860	12,420
Chips	4,510	5,130	9,590	—	750	610	—	4,380	8,990
Straw	4,960	6,170	12,740	—	100	400	—	6,060	12,340
Control	4,090	5,470	14,020	—	300	550	—	5,160	13,480
Hydromulch	5,330	6,020	14,430	—	730	1,020	—	5,290	13,410
Bark	5,030	7,470	9,420	—	1,310	1,230	—	6,170	8,200
Hay	4,580	6,640	9,040	—	610	910	—	6,030	8,130
FABIUS									
Petroset	4,140	—	8,060	3,070	—	2,160	1,080	—	5,980
Chips	6,180	—	23,100	210	—	40	5,970	—	23,060
Straw	2,540	—	8,290	350	—	940	2,200	—	7,350
Control	3,100	—	11,670	2,540	—	1,740	560	—	9,920
Hydromulch	4,000	—	14,920	1,640	—	990	2,360	—	13,940
Bark	4,450	—	21,980	2,220	—	190	2,230	—	21,790
Hay	8,650	—	18,270	1,310	—	410	7,340	—	17,860

Third season. Live vegetative cover was down severely the third year compared to the second-year cover on most plots partly because the legumes had lost most of their leaves just before measurement either from frost or drought. Nevertheless, vegetative cover increased on the control and Petroset plots. Despite this partial leaf loss, the legumes were still strongly predominant on all plots. If all litter, including mulch on the ground, was counted as a part of the total cover, then it is evident that the spoil surface is largely protected on all sites and ranged from 97 percent cover for the bark mulch to a minimum of 56 percent for the chip mulch.

Fourth season. Live cover was nearly double what it had been at the end of the third season. Legumes were still strongly predominant on all plots. There were no important differences in legume cover or total yields attributable to the mulches applied to any of the seven plots. The hydromulch, hay, and Petroset plots had appreciably more grass cover than the remaining plots.

Fifth season. Legumes were strongly predominant on all plots. There was no appreciable difference in the legume harvest between plots, but the grass harvest was nearly thirteenfold higher on the bark plot than on the straw plot. The total vegetation harvested ranged from 6 to 48 percent greater than the year before on all treatments.

Sixth season. No observations were made.

Seventh season. Legumes were still strongly predominant on all plots. Neither grass nor legume harvests were appreciably different on any of the seven plots. The total vegetation harvested in this seventh season (1982) ranged from 26 to 156 percent greater than that harvested in the fifth season. Grass yields were slightly higher in 1982 on the chip and bark plots than they had been in 1980, but had declined appreciably on the remaining five plots during the same interim.

Fabius Site

First season. Total vegetative growth was best on the hay plot (61 percent live cover), the bark plot (41 percent), and the straw plot (36 percent). Live cover on the chip, Petroset, hydromulch, and control plots was 25, 19, 19, and 16 percent, respectively. Legumes accounted for less than 12 percent of the live cover on all plots, but were most in evidence on the hay and bark plots.

Second season. Live vegetative cover increased through the second season on all except the straw plot where it decreased from 36 to 7 percent. The decline in live vegetation on the straw plot can be attributed to the wheat seed contained in the straw mulch. This seed germinated ahead of the planted seeds and produced a quick-growing lush cover that crowded out the seeded species. This dense cover of wheat died having produced little or no seed. Almost none of the planted seeds ever produced viable plants so the straw plot remained almost void of living vegetation, but with an even heavier accumulation of straw mulch than had initially been

Erosion and Transport of Suspended Solids

Erosion on the study plots was evaluated for a period of about a year and a half starting in the spring of 1976. The two methods of evaluation were: (1) erosion transect measurements, and (2) suspended solids measured in the runoff water.

In theory, the erosion transects should give a direct measurement of erosion from each plot. The data obtained from these transects are pre-

sented in Table 3 and seem to indicate that they sometimes measured something other than erosion. At both sites, the control had the most erosion as indicated by the transect measurements as would be expected. During measurements it was noted that the metal measuring pins frequently rested on clumps of sod, so did not penetrate all the way to the ground, thus sometimes causing the appearance of deposition when none had occurred.

Table 3.—Erosion as indicated by erosion transects and by suspended solids in surface runoff

Mulch ^a	Change in surface elevation ^b		Suspended solids ^c		Theoretical ^d suspended solids on standard plot	
	mm	Rank ^e	mg/l	Rank	mg/l	Rank
AYRGEM						
Petrosset	-7.8	6	2,334	4	584	3
Chips	-1.1	3	3,422	5	877	5
Straw	-0.7	1	4,225	7	1,124	7
Control	-12.3	7	1,765	2	506	2
Hydromulch	-0.9	2	3,612	6	943	6
Bark	-5.6	5	2,066	3	611	4
Hay	-2.6	4	1,681	1	453	1
FABIUS						
Petrosset	-5.4	6	8,834	5	2,343	6
Chips	-2.9	4	5,212	3	1,456	3
Straw	-2.1	3	1,178	2	229	2
Control	-10.3	7	9,257	6	1,627	4
Hydromulch	-3.9	5	13,280	7	2,744	7
Bark	+4.9	1	5,572	4	2,103	5
Hay	-0.5	2	868	1	215	1

^aMulches are listed in sequence from left to right, looking uphill.

^bChange in surface elevation relative to tops of erosion transect posts driven into the spoil. Negative values indicate erosion, positive values indicate deposition, swelling of spoil, or settling of the erosion transect posts into the spoil. These elevation changes are for the period May 19, 1976, to October 5, 1977, at Ayrgem and May 27, 1976, to May 3, 1977, at Fabius.

^cSuspended solids samples were effluent from small holes drilled in the side of each flume. These outlets were at elevations of 1-3/8, 2-3/8, 6, and 12 inches from the bottom of the flume. Suspended solids values presented here are average values for samples taken at all outlets during the major floods from August 4, 1976, to September 13, 1977, (2 to 8 samples per flume). Suspended solids concentrations averaged about the same from the four outlets at each flume.

^dTheoretical suspended solids that would have been found on a "standard" 9% slope, 72.6 feet in length. The adjustment to standard slope was made by dividing the measured suspended solids concentration by the LS factor in table 1. It is assumed that the ratio of suspended solids to erosion would remain the same on "standard" slopes as that observed for actual slopes—a rather debatable assumption.

^eRanked in order of increasing erosion or suspended solids.

lied. At the end of the second season, grass was still the predominant vegetation on all plots, though legumes had increased appreciably on bark and hay plots.

Third season. By the end of the third season, the bark, hay, and chip plots had the heaviest live cover (58, 52, and 52 percent, respectively). Live cover had increased on all except the bark and hay plots, both of which decreased from the previous season. The chip and straw plots both showed remarkable increases in live cover over the previous season, in both cases an increase almost totally attributable to the sudden establishment of a good stand of legumes which now was the dominant vegetation, 94 and 79 percent, respectively, of the total live cover. The other five plots were still predominantly grass, though the hay plot showed an appreciable legume concentration (47 percent of the live cover). The steep decline in grass on the chip and hay plots may have been caused by competition from the decomposers for available nitrogen.

Fourth season. There was no appreciable change in grass cover on any of the seven plots during the fourth season, but legume cover increased markedly on all plots. Legumes predominated on five of the plots by the end of this season: 97 percent of the vegetative cover on the chip plot, 89 percent on the straw, 71 percent on the hay, 66 percent on the hydromulch, and 51 percent on the Petrosset plots. Total yields and cover were highest on the hay plot.

Fifth and sixth seasons. No observations were made.

Seventh season. Legumes strongly predominated on all plots at Fabius by the end of the seventh season (92 percent). Legumes as a percent of total cover increased on all plots over that recorded for the fourth season and decreased from 72 percent on the Petrosset plot to essentially 100 percent on the chip plot. The grass yield was lower than it had been 3 years earlier on all except the straw plot.

The suspended solids content of water samples collected at the flumes was determined and should provide an independent, though indirect, measure of the relative rates of erosion on each plot. Average suspended solids concentrations are given in Table 3 and were collected in accordance with the procedure described in Table 3, footnote c.

Slope and length of plot vary enough to significantly affect erosion and, in turn, the suspended solids concentrations that were measured during the course of this study. If it is assumed that the suspended solids concentrations observed in runoff water are proportional to erosion on the watershed (not a completely valid assumption), then it is possible to adjust the observed suspended solids concentrations to what should have been present from plots of uniform slope and length. Using methods described by Wischmeyer and Smith (1965, p. 9), we corrected the observed suspended solids concentrations using the LS factors (Table 1) to give the theoretical concentrations shown in Table 3 to be expected from a "standard plot" 72.6 feet in length with a 9-percent slope.

At the Ayrgem site, the erosion transects indicated that the least erosion was on the straw, hydromulch, and chip plots, while the unadjusted suspended solids data indicated the

least erosion had been on the hay, control, and bark plots—or almost the reverse. Erosion deduced from the theoretical suspended solids concentrations expected on standard plots would have this same ranking, except that Petroset would replace the bark for third place. We believe that the suspended solids data are a better measure of erosion than the erosion transect data; but erosion as measured at the Ayrgem site by either of these methods cannot be explained in terms of physical characteristics of the mulches. However, the relatively dense vegetation on the bark and hay plots in 1976 and 1977 could account for the lower levels of suspended solids concentrations observed on these plots.

At the Fabius site the erosion transects showed an average of 4.9 mm deposition (or growth of sod) on the bark plot, while the hay, straw, and chip plots showed the least measured erosion. The unadjusted suspended solids data indicated that the least erosion was on the hay, straw, chip, and bark plots—pretty much in agreement with the erosion transect measurements, and in accord with what would be expected from erosion reducing mulches. Erosion deduced from the theoretical suspended solid concentrations expected on standard plots would have this same ranking except that the control would replace bark for fourth place.

Discussion

The response to a given mulch was not uniform from site to site. Numerous factors can contribute to this. In essentially all situations it seems likely that mulches help control erosion. In most instances, mulches help establish vegetation, but mulches can hinder, or even prevent vegetative growth. A discussion of the more important variables affecting mulch responses follows.

Variations Within a Given Mulch

Some mulches such as hydro-mulch may be uniform everywhere, yet most will vary greatly according to source. Bark, wood chips, and leaves can be from either hardwood trees or softwood trees, and they can be from either one tree species or from a mix of numerous tree species. Bark, wood chips, and leaves from some trees such as walnut may contain phytotoxic substances that actually repress plant growth. Allison and others (1963) found that finely ground wood or bark from 6 of the 28 species tested exhibited some degree of toxicity to garden peas. It is believed that the bark used at the Fabius site was predominantly softwood (conifer), while that used at the Ayrgem site was predominantly hardwood. Hardwood chips were used on both sites.

Hay used for mulch in the study area is usually a tall fescue hay that often contains mature seed of fescue

possibly some legume and weed seed. Seed from the hay would add to that which was deliberately sown and may account for the especially dense stand of fescue that quickly became established on the hay plot at the Fabius site.

The wheat straw used at the Fabius site contained much seed that produced plants that almost totally excluded those that were deliberately seeded to reclaim the spoil.

Weathering of Mulch Materials

Fresh mulch materials may have different effects from mulches that are allowed to weather or age for a year or two prior to application. The weathering of mulch materials may cause partial decomposition and thus reduce their erosion retarding properties somewhat, but at the same time, may reduce nutrient demand from the mulch material or promote release of nutrients from the mulch, thus improving the value of the mulch to growing vegetation. Weathering may gradually leach away any toxic components that may be in the mulch. Weathering also will likely reduce the viability of seeds contained in the mulch materials. Wood bark used at Fabius had weathered only a few months, while that used at Ayrghem had been exposed at a dump for more than a year. Straw and hay had weathered the bales for only a few months at both sites. Wood chips were applied the day they were chipped at the Ayrghem site, and were only a few months old when applied at the Fabius site.

Time of Application of Mulch and Seed

The effects of mulches on growth of vegetation may vary according to the season of seeding and time of mulch application relative to the date of seeding. Mulches tend to conserve moisture in the soil and to prevent extremes of temperature in the soil. Consequently, plants seeded in the hot or dry season are likely to benefit more from mulches than those seeded in a cool or moist season. Mulches applied in a cool or moist season may hinder the establishment of vegetation, though there is no evidence they did so at either of the sites investigated in this study.

Mulches were applied from 1 to 23 days after seeding in this study, and germination of seeds may have been different had each mulch been applied at a different time. Most seeds should have germinated by the time the bark and chips were applied to the Ayrghem plots 23 days after seeding, so only a post-germination effect due to these mulches could be observed. At Fabius, bark and chips were applied the day after seeding, so both pre- and post-germination effects of these mulches should have been observed here. Jim Powell³ surmises that the natural organic substances produced by bark or wood chips will scarify the seeds of hard seeded legumes such as the lespedezas, thus speeding up their germination. Therefore, at Fabius we may be observing the chemical effects as well as physical effects of these mulches.

³Jim Powell, Peabody Coal Co., Greenville, Kentucky. Personal communication August 4, 1983.

Effect of Applied Fertilizers on Observed Plant Growth

The initial heavy application of nitrogen fertilizer would be expected to favor growth of grasses over legumes. After a year or two when the nitrogen is leached from the spoil or tied up in organic material, legumes, because of their ability to supply their own nitrogen, would have a distinct advantage over the grasses. The first year's growth on all plots at the Fabius site and on three plots at the Ayrghem site was predominantly grass as had been expected. Grasses still predominated at all Fabius plots the second year. Legumes predominated the first year on four of the Ayrghem plots; namely, bark, chips, straw, and hay—those with the greatest mass of added organic materials. These four mulches not only seemed to retard the growth of grasses, perhaps by competing for nutrients as discussed in the next section, but they also generally promoted a growth of legumes more than adequate to compensate for any possible suppression of grasses.

Demand of Mulch Decomposers for Nutrients

All organic mulch materials will eventually decompose, and as they do so, the microorganisms that digest them extract nutrients from the spoils they contact. Partially decomposed mulches and coarse textured mulches are likely to be less demanding of nutrients than are unweathered or finely divided mulches. Mulch-decomposing bacteria demand nutrients, especially nitrogen, and are in direct competition with growing plants; and plant growth may be severely retarded by this competition. In the reclamation of mine spoils, it is common practice to apply enough

fertilizer to supply the needs of growing plants for the first year or two, but not necessarily enough for the needs of mulch-decomposing bacteria. Eventually a shortage of nitrogen is likely to develop on spoils that are being mulched during reclamation, unless they have been seeded to nitrogen fixing legumes. At the Fabius site, a severe shortage of nitrogen seems to have developed on the wood-chip and straw plots by the third year. This may account, at least in part, for the great increase in legume cover on these sites during the third year and the relative or absolute decline in grass cover.

Aspect

The potential value of a given mulch depends greatly on the aspect of the slope to which it is applied. A slope facing south or west is much more likely to benefit from the cooling and moisture retaining characteristics of a mulch than one facing north or east. The greater insolation on southerly and westerly slopes generates higher soil temperatures and causes the slopes to be much more droughty. A heavy mulch applied to a northerly or easterly slope may retard the establishment of vegetation, especially during the cooler or damper months.

The aspect of each plot is given in Table 1. The Ayrghem plots slope in a northeasterly direction; nevertheless, mulches still had a beneficial effect at this location because the Ayrghem spoils were very sandy and tended to be droughty. They were seeded late enough in the season for moisture to be less than optimum, so the moisture conserved by the mulches was beneficial in establishing a good plant cover.

The Fabius plots face west toward a high wall that shields the lower portions of the plots from the full effect of the late evening sun. Mulches at Fabius had a beneficial effect.

Spoil Physical Characteristics

Data on particle-size distribution, spoil texture, and moisture retention characteristics are given in Table 4. Despite the striking differences in available water, Figure 2 and Table 2 show that overall vegetative growth was similar at the Ayrghem and Fabius sites. The Ayrghem spoils perhaps compensated for the lower percentage of available water with a deeper root zone and greater permeability. The greater percentage of coarse fragments in the Fabius spoil would also have been a compensating factor.

Spoil Chemical Characteristics

A summary of selected spoil chemical characteristics is given in Table 5 for the years 1976, 1977, and 1982-83. Specific conductance and sulfate measurements indicate that both the Ayrghem and Fabius sites contain relatively low and decreasing concentrations of dissolved solids.

Median pH values (from Table 5) of all seven plots at the Ayrghem site averaged 6.9 in all three sets of spoil samples. Median pH values from the Fabius site averaged 5.0, 4.8, and 5.3, respectively, for the 1976, 1977, and 1982 spoil samples. The pH shifts over time in the Fabius spoil cannot be readily explained, but may be attributable largely to the difficulty in obtaining samples fully representative of these highly variable spoils. After almost 7 years, the chip plot at Fabius had the highest biomass as shown in Table 2; yet, it had one of the lowest pH levels (Table 5), a pH that in agronomic circles is considered just barely adequate for good plant growth. Data in Table 5 indicate that appreciable increases in exchangeable acidity and exchangeable aluminum occurred on the Fabius plots between 1977 and 1982 and that the site might benefit from a light application of lime.

Table 4.—Summary of spoil texture, particle-size distribution, and moisture retention characteristics at 0–6 inch depth, 1982–1983 samples, in percent

Treatment ^a	Coarse fragments	Particle-size distribution of soil fraction			Spoil texture	Moisture retention by soil fraction		Available water in soil fraction ^b
		Sand	Silt	Clay		1/3 bar	15 bars	
AYRGEM								
Petroset	21	82	12	6	Gravelly sandy loam	8	2	6
Chips	20	81	13	6	Gravelly sandy loam	8	2	6
Straw	16	82	12	6	Gravelly sandy loam	8	2	6
Control	25	80	12	8	Gravelly sandy loam	8	2	6
Hydromulch	19	82	11	7	Gravelly sandy loam	8	2	6
Bark	10	84	11	5	Sandy loam	7	2	5
Hay	16	82	11	7	Gravelly sandy loam	8	2	6
FABIUS								
Petroset	38	58	33	9	Very gravelly sandy loam	20	7	13
Chips	38	58	31	11	Very gravelly sandy loam	18	9	9
Straw	40	54	35	11	Very gravelly sandy loam	18	7	11
Control	45	52	35	13	Very gravelly sandy loam-loam	17	7	10
Hydromulch	40	52	37	11	Very gravelly sandy loam-loam	18	8	10
Bark	36	55	34	11	Very gravelly sandy loam	21	8	13
Hay	47	48	39	13	Very gravelly loam	18	7	11

^aPlot sequence is from left to right when viewed looking uphill.

^bWater available for plant use was assumed to be equal to the difference in moisture retained at 1/3 bar and at 15 bars pressure.

Table 5.—Summary of spoil chemical characteristics at 0-6 inch depth:
March to April 1976; August 1977; October 1982 to March 1983

Treatment	Median pH ^a			pH ^a extremes			Mean specific conductivity ^a			Mean sulfate ^b			Mean exchangeable acidity			Mean exchangeable aluminum		
	1976	1977	1982-83	1976	1977	1982-83	1976	1977	1982-83	1976	1977	1982-83	1976	1977	1982-83	1976	1977	1982-83
	</																	

^aDetermined on 1:2 spoil to water extracts (air-dry basis).

^bDetermined on 1:10 spoil to water extracts.

Conclusions

In general, bark mulch was the most satisfactory of the six mulches and peat mulch followed closely. Petro- and hydromulch plots generally differed little from the control.

No one mulch is best for all spoils and for all purposes.

Due to the great variability within certain types of mulch materials such as straw, hay, leaves, and wood bark must be taken into consideration when selecting a mulch.

Use of inappropriate mulch may have negative effects on some or all forms of vegetation.

The use of mulches high in organic matter such as bark, chips, hay, and straw tends to encourage the growth of legumes more than grasses.

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Dyer, Kenneth L.; Curtis, Willie R.; Crews, Jerry T. **Response of vegetation to various mulches used in surface mine reclamation in Alabama and Kentucky—7-year case history.** Gen. Tech. Rep. NE-93. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1984. 11 p.

Five different mulches and one mulch-amendment combination were evaluated in the reclamation of two different mine spoils, one in western Kentucky and one in northern Alabama. The treatments evaluated were bark, hardwood chips, straw, hay, hydromulch, and hydromulch plus Petroset SB emulsion. After 7 years, the effects of the different mulch treatments were readily apparent at the Alabama site where the hardwood-chip plot had strikingly superior cover. Differences were not so apparent at the Kentucky site.

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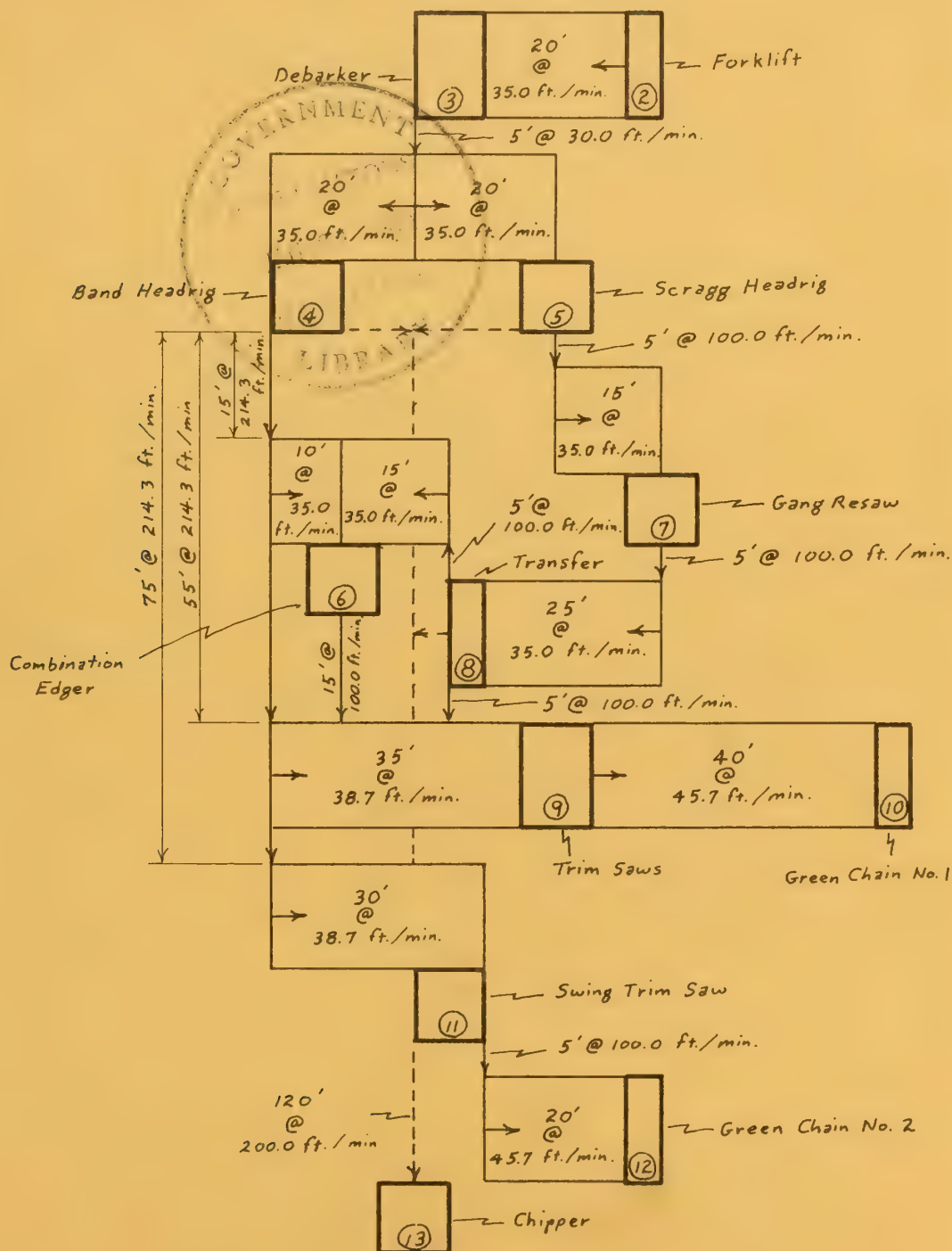
Keywords: Mulch, reclamation, surface-mine, spoils, Alabama, Kentucky, legumes, grasses, bark, hardwood chips, straw, hay, hydromulch, petroset SB emulsion, erosion.

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DESIM User's Manual: A Procedural Guide for Designing and Simulating Hardwood Sawmill Systems

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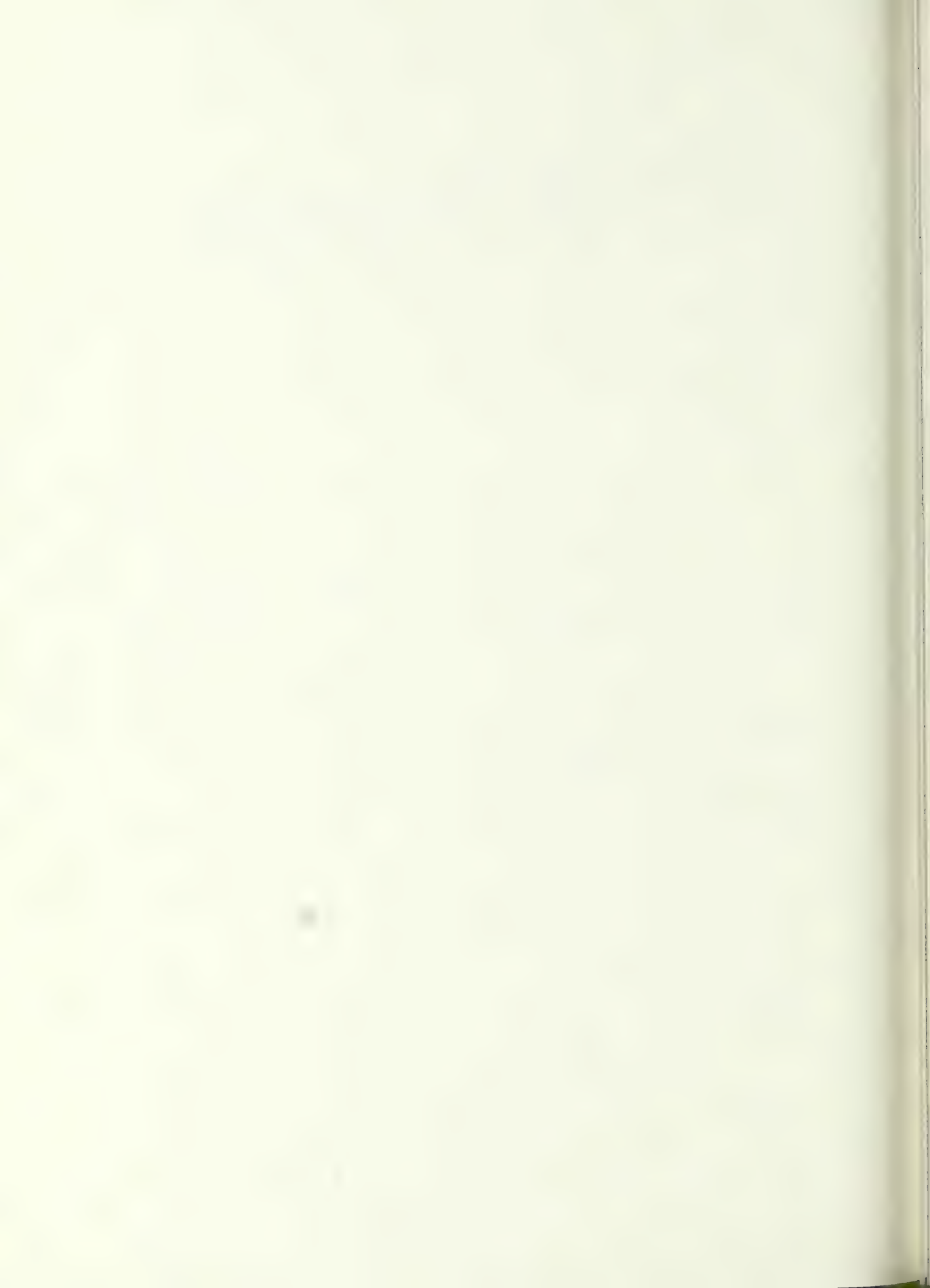
Abstract

A procedural guide for using the DESIM computerized system for designing and simulating the operation of hardwood sawmill systems. Instructions are provided for: (1) setting up the DESIM system on the computer, (2) obtaining the necessary data forms, (3) filling out the data forms to represent a proposed sawmill system, (4) getting the data from these forms into a sawmill data file, and (5) simulating the operation of the proposed sawmill. This user guide makes the system relatively easy to use for even complex sawmill situations.

DESIM User's Manual: A Procedural Guide for Designing and Simulating Hardwood Sawmill Systems

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Introduction

DESIM¹ (DESign SIMulator), a computerized system for designing and simulating the operation of hardwood sawmills, can be used to design new mills or to plan the modification of existing mills. It can handle complex situations and a wide variety of different products. And, once a mill has been designed and simulated, the design can easily be changed and simulated again to investigate different possibilities.

The DESIM system consists of three computer programs and two support data files. The first program provides data sheets for recording the required sawmill information. The second program provides an interactive question and answer procedure for getting the information from the data sheets into a sawmill data file. And, the third program uses this data file to realistically simulate the operation of the proposed sawmill. DESIM was designed to make it as easy as possible to use.

This paper provides a systematic procedure for using the system. However, it is important that you have a good general understanding of the system before working through the procedure. To gain this understanding, I suggest reading "DESIM: A System for Designing and Simulating Hardwood Sawmill Systems" (Adams 1984). This suggested paper provides a general discussion of the system and what it will do.

Along with the need for a general understanding of the system, several other requirements must be met before using the system. First, you must have available a large mainframe computer such as those available at most universities. The largest program in the system requires 1.6 megabytes of internal storage to run. Second, because the system uses the GASP-IV FORTRAN-based simulation language, the GASP-IV package (Pritsker 1974, 1977) must be available at your computer facility. Third, a conversational monitor system (CMS) computer terminal must be available and connected to the computer either directly or through a data communication modem. And fourth, you must obtain a copy of the DESIM computer tape. This tape is available from the Forestry Sciences Laboratory, Northeastern Forest Experiment Station, P.O. Box 152, Princeton, West Virginia 24740.

¹The computer programs described in this publication are available on request with the understanding that the U.S. Department of Agriculture cannot assure their accuracy, completeness, reliability, or suitability for any other purpose than that reported. The recipient may not assert any proprietary rights thereto nor represent them to anyone as other than Government-produced computer programs.

Procedure

Once the above requirements have been met you are ready to work through the DESIM procedure, which is discussed as follows:

1. **SETTING UP DESIM**—Provides instructions for getting the DESIM computer tape information into your user files and setting up the necessary control files.
2. **SETTING UP A SAWMILL SYSTEM**—Discusses the preliminary work required to set up a proposed sawmill system to be simulated.
3. **RUNNING FORMS PROGRAM**—Provides instructions for obtaining the necessary data forms to be filled out for the sawmill system.
4. **FILLING OUT DATA FORMS**—Provides instructions for filling out the data forms correctly to reflect the sawmill system.
5. **CREATING RAW MATERIAL DATA FILES**—Provides instructions for creating any needed raw material data files.
6. **RUNNING DESIGN PROGRAM**—Discusses the running of the DESIGN program to get the information from the data forms into a mill data file.
7. **RUNNING THE SIMULATION (SIMU) PROGRAM**—Discusses the running of the SIMU program to simulate the actual operation of the proposed sawmill system.
8. **MODIFYING THE SAWMILL SYSTEM**—Discusses the procedure for modifying a sawmill system after it has been simulated.

If this systematic procedure is followed carefully, little difficulty should be encountered when using the system. Actually, after using the system several times, you will find it surprisingly easy to use. This is especially true when you consider its capabilities.

1. Setting Up DESIM

This section provides the procedure for transferring files from the DESIM computer tape to your CMS files and for developing the computer control files needed to use the DESIM system. If you are not familiar with the procedures for transferring computer files or for setting up programs to run on the computer, this section will mean little to you. However, consultants at your computer center can use this section to set up the system for you.

If you are using an IBM² computer, see Appendix A for detailed instructions, job control language (JCL), and execution (EXEC) statements required to set up the system. For other computers, you or a consultant must set up the system based on the following discussion.

²The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture or the Forest Service of any product or service to the exclusion of others that may be suitable.

In this discussion, IBM file designations will be used. Each file designation consists of a file name, file type, and file mode. For example, the file "FORMS FORTRAN A1" has a file name of "FORMS", a file type of "FORTRAN", and a file mode of "A1." If you are not using an IBM computer, you may have to change these designations to meet the requirements of your computer.

1.1 Tape to CMS file. The DESIM system is on a 9-track computer tape at a density of 1600 bits per inch. It is in a nonlabeled, fixed block format with a record length of 80 and a block size of 6000. The information on the tape consists of five files (three computer programs and two data files). Use the following procedure to move the tape information to CMS files.

- FORMS Program—Move this program from the first tape file location to the CMS file with the designation "FORMS FORTRAN A1."
- DESIGN Program—Move this program from the second tape file location to the CMS file with the designation "DESIGN FORTRAN A1."
- SIMULATION Program—Move this program from the third tape file location to the CMS file with the designation "SIMU FORTRAN A1."
- Equipment Data File—Move this file from the fourth tape file location to the CMS file with the designation "EQ DATA A1."
- Lumber Grade Data File—Move this file from the fifth tape file location to the CMS file with the designation "LGR DATA A1."

1.2 CMS Execution Files. To facilitate the running of the three DESIM computer programs, CMS EXEC files and JCL files should be created. The EXEC files execute the CMS command procedure necessary for running the programs from the CMS terminal. The JCL files provide the required job control statements when the programs are sent to a multiple virtual storage (MVS) operating system for processing. The discussion of the files required for each DESIM program follows:

- FORMS Program—Create an EXEC file that will submit the "FORMS FORTRAN A1" file and the required JCL file to the MVS operating system for running. In generating the JCL file, if time and region parameters are required, set time equal to 1 minute and set region equal to 150K. If you want the resulting output sent directly to a printer, this should also be specified in the JCL file. If the output is sent to the user reader file, you must then manually enter the required information at the terminal to send the output to a printer.

- **DESIGN Program**—This program requires only an EXEC file for the CMS system. Since it is not sent to MVS operating system, no JCL file is required.

In creating the EXEC file, assignments must be made for the input-output unit numbers used in the program. The assignments by unit numbers are:

- 03—"MILL DATA A1" file input (disk)
- 04—"EQ DATA A1" file input (disk)
- 05—Terminal input (keyboard)
- 06—Terminal output (video screen)
- 09—"MIL2 DATA A1" file output (disk)
- 11—"MAT1 DATA A1" file input (disk)
- 12—"MAT2 DATA A1" file input (disk)
- 13—"MAT3 DATA A1" file input (disk)
- 14—"MAT4 DATA A1" file input (disk)
- 15—"MAT5 DATA A1" file input (disk)
- 16—"GAS DATA A1" file output (disk)

Once assignments have been made for the input-output unit numbers, enter statements for loading and running the DESIGN program. Following these statements, enter statements to perform the following:

- Determine if a "MILL DATA A1" file exists
 - Erase the "MILL DATA A1" file if it exists
 - Rename the "MIL2 DATA A1" file to "MILL DATA A1"
 - Determine if a "GASP DATA A1" file exists
 - Erase the "GASP DATA A1" file if it exists
 - Rename the "GAS DATA A1" to "GASP DATA A1"
- **SIMULATION Program**—Create an EXEC file that submits to the MVS operating system the following files:
 - Required JCL file
 - SIMU FORTRAN A1
 - GASP DATA A1
 - MILL DATA A1
 - LGR DATA A1

In generating the JCL file, if time and region parameters are required, set time equal to 5 minutes and set region equal to 1600K. If you plan to check the simulated output before having it printed, also specify in the JCL that the output is to be sent to the reader file.

Setting Up a Sawmill Situation

Whether designing a new mill or planning the modification of an existing mill, the entire sawmill situation must be considered. Include not only the physical attributes of the mill, but also the raw material inputs, the product outputs, and the processing procedures. In this section, I will discuss a procedure for setting up such a sawmill situation when using DESIM to help evaluate a mill design or modification.

2.1 Diagram proposed mill. Start by drawing the mill layout roughly to scale. Figure 1 shows a sample layout. Notice in this figure that the machine centers have been labeled and numbered. When numbering the machines, use numbers 2 through 30. The number "1" cannot be used. Also notice that the lengths and speeds of both the conveyors and buffers (surge decks) have been indicated. By drawing such a diagram, you can make sure that the link ups between machines have been properly considered. And, the information on the diagram will be readily available when needed later.

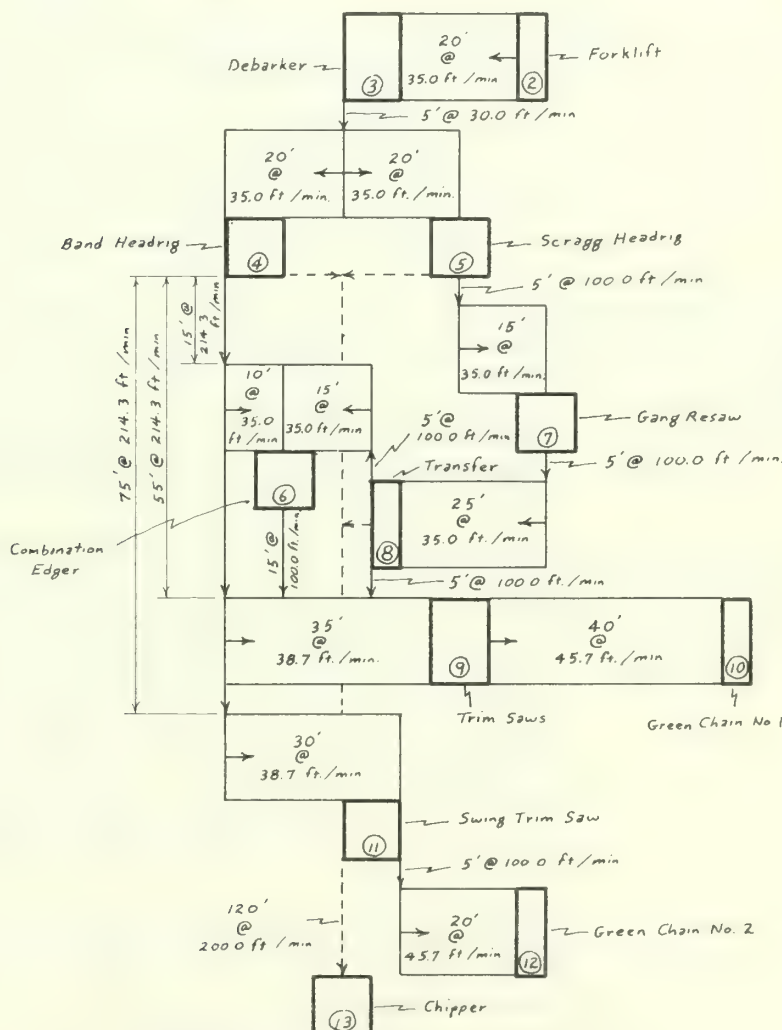


Figure 1.—Sample sawmill layout.

2.2 Raw material considerations. Do not underestimate the importance of raw material inputs when designing a new or planning the modification of an existing sawmill. The species, quality, and sizes of raw material to be processed are very important when determining the best new, or modified mill for a given sawmill situation. Raw material inputs to the DESIM system can be: (1) actual piece data, (2) sawlog frequency distributions, and/or (3) bolt frequency distributions. If the necessary raw material inputs are not available for a given sawmill situation, you will have to collect the data and process it into one or more of the three types of raw material inputs.

For each log and/or bolt deck considered in a design, one of the three types of raw material input data will be required. There is no limit to the number of these input decks that can be considered. However, each deck can accept only one data set from only one of the three input data types.

2.3 Processing and product considerations. Before you get involved in the mechanics of filling out data forms, you should decide exactly how the material is going to be processed through the proposed mill to produce the desired products. In making these decisions, do not miss any processing steps or mill products. This is an important part of the process and will take time. As you make a processing decision, write it down as an instruction. This list of instructions can then be used later when filling out data forms to assure that you do not miss anything. For the sawmill in Figure 1, these instructions might include:

- Forklift (2)
 - All logs sent to debarker (3).
- Debarker (3)
 - All logs ≤ 12 inches in scaling diameter leaving the debarker (3) will go to the Scragg headrig (5). However, if the Scragg buffer is full, these logs can go to the band headrig (4).
 - All logs > 12 inches will go to the band headrig (4).
- Band headrig (4)
 - All logs are to be sawed around for grade to either a tie or cant for resawing.
 - Fifty percent of all Grade 2 and Grade 3 logs ≥ 16 inches in scaling diameter and ≥ 9 feet in length will be sawed to 7- by 9-inch ties.
 - All logs that do not fit the above category will be sawed to a cant for resawing. Those ≤ 16 inches in scaling diameter will be sawed to 6-inch-thick cants. Those > 16 inches in scaling diameter will be sawed to 8-inch-thick cants. None of these cants can be wider than 12 inches.
 - All square-edged boards produced on the band headrig (4) will be sent to the trimsaws (9).
 - All wane-edge boards will be sent to the combination edger (6).
 - Ties will be sent to the swing trimsaw (11).
 - Cants will be sent to the gang side of the combination edger (6).
 - Slabs will be sent to the chipper (13).

- Scragg headrig (5)
 - All logs processed by the Scragg headrig (5) will be processed into 6-inch-thick 2-sided cants and sent to the gang resaw (7).
 - Slabs will be sent to the chipper (13).
- Combination edger (6)
 - All parts sent to trimsaws (9).
- Gang resaw (7)
 - The square-edged boards sent from the gang resaw (7) to the transfer station (8) will be transferred to the trimsaws (9).
 - The wane-edged boards sent from the gang resaw (7) to the transfer station (8) will be transferred to the combination edger (6).
 - The slabs sent from the gang resaw (7) to the transfer station (8) will be transferred to the chipper (13).
- Transfer station (8)
 - The wane-edged boards sent to combination edger (6).
 - The square-edged boards sent to trimsaws (9).
- Trimsaws (9)
 - All parts sent to green chain No. 1 (10).
- Swing trimsaw (11)
 - All ties sent to green chain No. 2 (12).

You may have noticed that neither bark nor sawdust were considered in the above instructions. These products are not considered in the DESIM process because they do not usually affect the production and flow of the primary products in a sawmill operation. Also, the routing and chipping of trimming and edging material are not considered for the same reason. However, the trimming and edging volumes are included in the simulated chip yields.

Running FORMS program

The FORMS program is set up so that you can specify the data forms wanted as well as the number of each needed. This is done by taking the "FORMS FORTRAN A1" file into the edit mode on your CMS terminal. When this is done, you will find a listing of the 22 different data forms. The statements in the listing appear as:

```

FORM NO. 1—RAW MATERIAL ACTUAL PIECE DATA
IFOR1=1
FORM NO. 2—MILL DESIGN
IFOR2=1
:
FORM NO. 22—CRITERIA FOR ROUTING MATERIAL
IFOR22=1
  
```

The statement "IFOR1 = 1" below the statement "FORM NO. 1—RAW MATERIAL ACTUAL PIECE DATA" indicates that only one Form No. 1 will be produced. If five of these forms are needed, change "IFOR1 = 1" to "IFOR1 = 5". But, if you do not need this form, change "IFOR1 = 1" to "IFOR1 = 0". Repeat the procedure for each form in the listing. I should point out that until you become familiar with the DESIM system, it will be difficult for you to know exactly how many of each form you will need. However, if at any time more forms are needed, rerun the FORMS program.

Once the "FORMS FORTRAN A1" file has been changed to indicate the forms required, save it in your CMS file. At this point, run the FORMS program by entering the word "FORMS" at the CMS terminal. Upon completion of the run, the forms output will be sent to your CMS reader file. You can then send the forms to the printer.

4. Filling Out Data Forms

The following discussion deals with the filling out of the 22 different data forms. In using the DESIM system you will fill out only the forms needed to represent your proposed sawmill situation. Samples of each form are shown in Appendix B. Some of these forms will be referred to as the various inputs are discussed.

4.1 Form No. 1—Raw material actual piece data. Use this form only if actual piece data is used as raw material input to the sawmill situation. As many as five different data sets of this type can be included as input. However, only one data set can be used as input at a given point in the mill. A discussion of the information required on the form follows:

- DATA SET NO.—Number (1 through 5) of the particular data set of this type.
- MATERIAL TYPE CODE—These codes are:
 - 1—Long-length pieces to be bucked into standard sawlogs (can also include standard logs).
 - 2—Long-length pieces to be bucked into standard sawlogs and bolts (can also include standard sawlogs and bolts).
 - 3—Standard sawlogs only.
 - 4—Bolts only.
- PIECE NUMBER—The log or bolt identification number. If a long-length piece has four logs and/or bolts in it, the logs and/or bolts are listed separately on the form with the same PIECE NUMBER for each (see shaded area on Form No. 1 in Appendix B).

- SPECIES CODE—Codes for the 12 species available in the DESIM system are:

- 1—Northern red oak
- 2—Black oak
- 3—Scarlet oak
- 4—White oak
- 5—Chestnut oak
- 6—Sugar maple
- 7—Red maple
- 8—Yellow-poplar
- 9—Basswood
- 10—Black cherry
- 11—Yellow birch
- 12—Beech

- GR—Grades 1 through 3 are the standard USDA Forest Service hardwood factory-lumber log grades. Grade 4 is used for subfactory logs. And, Grade 5 is used to indicate bolts. The lumber grade yields for sawlogs processed in the DESIM system are based on log Grades 1 through 4. Therefore, when the proposed sawmill is to produce grade lumber, these standard log grades must be used.
- SMALL DIAM.—Scaling or small-end diameter of log or bolt in inches.
- LARGE DIAM.—Large end or butt diameter of log or bolt in inches.
- LENGTH—Length of log or bolt in feet.
- CO—This code identifies individual logs and bolts when they are not part of a long-length piece. And, for long-length pieces, it identifies the position of the different logs and/or bolts (see shaded area on Form No. 1 in Appendix B). The codes are:

- 1—A log or bolt that is not part of a long-length piece.
- 4—The small-end log or bolt of a long-length piece.
- 6—An intermediate log or bolt of a long-length piece.
- 9—The large-end log or bolt of a long-length piece.

The large-end piece is always entered first, and the small-end piece entered last for a long-length piece.

4.2 Form No. 2—Log species, grade, and size distributions. Use this form when frequency distributions are used as sawlog inputs to the proposed sawmill situation. As many as five separate data sets of this type can be used. Each of these data sets can have distributions for as many as five species. As with the actual piece data, only one data set can be used as input at a given point in the mill. A discussion of the information required on this form follows:

- DATA SET NO.—Number (1 through 5) of the particular data set of this type.
- SPECIES—The following information is needed for each species in the data set.
 - CODE NO.—Code number of species for which log frequency distributions are included. (See species codes given in instructions for Form No. 1.)
 - PERCENT—The number of logs, in percent, of each species found in the data set.
 - LOG TAPER/FOOT—Average log taper, in inches, per foot used to calculate butt diameters of logs generated from these distributions.
 - PERCENT OF LOG GRADE—The number of logs, in percent, found in each log grade for a species. Grades 1 through 3 are standard USDA Forest Service hardwood factory-lumber logs. And, Grade 4 represents subfactory logs.
 - PERCENT OF LOGS BY DIAMETER CLASS—The number of logs, in percent, found in each diameter class from 8 to 24 inches for a given species and grade.
 - PERCENT OF LOGS BY LENGTH CLASS—The number of logs, in percent, found in each length class from 8 to 16 feet for a given species and grade.

4.3 Form No. 3—Bolt species and size distributions. The instructions for filling out this form are the same as those for Form No. 2. The only difference is that bolt-grade percentages are not required. As many as five separate data sets of this type can be used. Each data set can have bolt frequency distributions for as many as five species. As with sawlog frequency distributions, only one data set can be used as input at a given point in the mill.

4.4 Form No. 4—Mill design. Use this form to record preliminary information for the proposed sawmill situation and to record the data set numbers and types when actual piece data are used as raw material input. A discussion of the required information follows:

- PROJECT NAME—Name or designation of the proposed sawmill situation.
- PROJECT NO.—Number of the particular approach for a given sawmill situation. Several different approaches may be tried for a given situation. By numbering these approaches, the output for the different runs can be identified at a later date.
- NUMBER OF RUNS—The number of simulated runs wanted for a given approach to a sawmill situation. Each run is made with a different set of random numbers. This allows you to check the operation of the mill as factors such as processing times, down times, and raw materials vary according to frequency distributions.

- **RUN TIME**—The operating time, in minutes, for each simulated run of the proposed sawmills. For example, for an 8-hour operating shift, the **RUN TIME** would be 480 minutes minus break times and other scheduled down times.
- **PURGE TIME**—The number of minutes before quitting time that the headrig or headrigs are to be shut down to allow the material following the headrig to be purged from the system. When this time occurs while a headrig is processing a log or bolt, the processing of that log or bolt will be finished before the headrig shuts down.
- **UNBLOCKED MILL RUN? (N/Y) Enter:**

Y—If the machines are not to be blocked. In this instance, surge decks are allowed to expand to accommodate the material being sent to them. The DESIM output then indicates how long the surge decks must be to prevent blocking.

N—If the machines are to be blocked when the down stream surge decks are full. The DESIM output then indicates how many times each machine was blocked and the total time they were blocked.

- **ACTUAL LOG AND/OR BOLT DATA**—If no actual piece data are used as input to the proposed sawmill situation, nothing is entered here. However, if actual piece data are used, the “DATA SET NO.” and the “MATERIAL TYPE CODE” for each data set are entered here.

4.5 Form Nos. 5 to 19—Machine data. Much of the information on the **MACHINE DATA** forms is the same, so the discussion of Forms 5 through 19 is combined. When the explanation differs for a given piece of information, that difference will be shown by form number. As stated in the following discussion, some information will be required only on certain forms.

- **MACHINE NO.**—The machine number taken from the proposed sawmill layout diagram.
- **MACHINE NAME**—The machine name taken from the proposed sawmill layout diagram. Where there is more than one machine of a given type, you might want to add numbers to the names. For example, if you have two headrigs, you might name them Headrig No. 1 and Headrig No. 2. These names are used to identify the DESIM output to the individual pieces of equipment.

- **MACHINE CODE**—On most forms, this code is already given. However, on Form Nos. 5, 7, 8, and 11 you must supply the code.

FORM NO. 5—The machine codes are:

- 1—Forklift.
- 2—Crane.

FORM NO. 7—The machine codes are:

- 4—For debarkers with processing time related to area of log or bolt (rosserhead, etc.).
- 5—For debarkers with processing time related to length of log or bolt (ring-type, etc.).

FORM NO. 8—The machine codes are:

- 6—Circular saw headrig.
- 7—Bandsaw headrig.
- 8—Circular saw headrig with vertical edger.
- 9—Bandsaw headrig with vertical edger.

FORM NO. 11—The machine codes are:

- 12—Standard edger.
- 13—Combination edger (board and gang cant).

- **RAW MATERIAL CODE**—These codes are used only on Form No. 5. Use to indicate the type of raw material data providing material to the input machine. The codes are:

- 0—Actual piece data.
- 1—Log frequency distribution data.
- 2—Bolt frequency distribution data.

- **RAW MATERIAL DATA SET**—This data set number is taken from Form Nos. 1, 2, or 3, and entered only on Form No. 5 to indicate the data set providing material to the input machine.
- **HEADRIG ORDER NO.**—This number is required only on Form Nos. 8, 9, and 10. Besides the machine number, each headrig also must be given a headrig order number. The actual order is not important so long as the numbers run consecutively from 1 through 5.

- **PROCESSING TIMES AND RATES**—The information can be by species or for all species combined. If you do not wish to use the processing times and/or feed rates in the equipment data file or if the file does not have the information required for the machine you are using, you must provide your own on the form. However, if you use the equipment data file information, enter only the TIME CODE and SPECIES CODE information in this processing times and rates section. You can determine what information is available in the equipment data file by obtaining a listing of EQ DATA A1.

- **TIME CODE**—These codes are:

0—Times and rates are different by species.

1—Times and rates are the same for all species.

- **SPECIES CODE**—If a “1” has been entered for the TIME CODE, only one set of processing times and rates must be considered. So a “1” is entered as the SPECIES CODE. If a “0” has been entered for the TIME CODE, individual species codes are entered for each set of processing times and rates data for the species to be processed. The species codes are shown in the discussion of Form No. 1.
- **PROCESSING TIME**—Enter time in minutes on Form Nos. 5, 15, 16, 18, and 19. On Form No. 7, if the processing time is for a rosserhead-type debarker, it is entered as minutes per 10 square feet of surface area.
- **FEED RATE**—Enter rate as feet per minute on Form Nos. 7, 9 to 14, and 17. On Form No. 6, this rate is entered as inches per minute.
- **PROCESSING TIME DISTRIBUTION**—The parameters for lognormal frequency distributions include: (1) mean, (2) minimum value, (3) maximum value, and (4) standard deviation. If the required lognormal parameters for any of the following times are not available in the equipment data file or if you do not wish to use the available parameters, you must develop your own.

To develop satisfactory lognormal parameters, your data set should contain at least 30 observations. Once the data have been collected, the simple procedure discussed here can be used to provide the parameters. First, calculate a constant by multiplying the smallest value in the data set by 0.95. Second, transform each value in the data set by subtracting the constant and taking the natural log of the result. Third, for this transformed data, calculate the mean and standard deviation. This can be done on any calculator that has a mean and standard deviation routine. These are the required lognormal mean and standard deviation parameters. Fourth, the required minimum value parameter is obtained by subtracting the above constant from the smallest value in the untransformed data and taking the natural log of the result. Finally, the required maximum value parameter is obtained by subtracting the constant from the largest value in the untransformed data and taking the natural log of the result. An example of this procedure is shown in Appendix E.

- **LOAD TIME**—This input is required on Form Nos. 6 to 10 and 12 to 14. The lognormal parameters for this time are based on the time required to load material into a machine. Since load time is not a factor for some machines, it is not required on all forms.
- **BOARD LOAD TIME**—This time distribution is used only on Form No. 11 for edgers and combination edgers. The lognormal parameters are based on the times required to load boards into the edger; that is, the time from when a board leaves the edger until the next board hits the saws. These times should only reflect the situation when boards are readily available to the operator.
- **CANT LOAD TIME**—This time distribution is used only on Form No. 11 for combination edgers. The lognormal parameters are based on the time to load cants into the combination edger; that is, the time from when a cant leaves the edger until the next cant hits the saws. These times should only reflect the situation when cants are readily available to the operator.
- **TURN TIME**—This time distribution is used only on Form No. 8 for band and circular headrigs. The lognormal parameters are based on the time required to turn logs or bolts on the carriage. This time starts when the carriage stops for the piece to be turned and stops when the piece has been turned and the carriage starts forward.
- **SLAB TIME**—This time distribution is used only on Form No. 8 for band and circular headrigs. The lognormal parameters are based on the time required to slab a log or bolt divided by the length and the resulting value multiplied by 10 to scale it for calculation purposes. The time begins when the carriage starts forward and ends when the carriage returns and stops.
- **LINE TIME**—This time distribution is used only on Form No. 8 for band and circular headrigs. The lognormal parameters are based on the time required to saw a line divided by the length of the log or bolt and the resulting value multiplied by 10 to scale it for calculation purposes. The time begins when the carriage starts forward and ends when the carriage returns and stops.
- **DOWN TIME**—This input is required on Form Nos. 5 to 19. The lognormal parameters for this time are based on the nonscheduled down times for a machine. These down times include only those resulting from (1) the machine or operator not being ready, (2) the machine's surge deck being down, or (3) the machine's down stream conveyors being down. Times are not included when the machine is idle from lack of available material to process or the machine is blocked because the system following it is jammed.
- **PERCENT DOWN**—This input is required on Form Nos. 5 to 19 and is the frequency that the machine is expected to go down. In other words, at 5 percent, the machine will go down an average of 5 out of every 100 times a piece is to be processed. Once the machine goes down, the down time lognormal frequency distribution discussed above is used to determine how long it will be down.

- **PRODUCT LENGTH DISTRIBUTION**—This input is required only on Form No. 19 for machine centers producing special products. It allows up to five different product lengths in inches. For each length, the user must also supply the percentage of products wanted. This is set up to allow the cutting of long pieces into shorter products such as headers and half headers used in coal mines.

4.6 Form No. 20—Headrig sawing instructions. This form provides the instructions for breaking down log and/or bolts into various products. At least one set of instructions is required for each headrig. However, as many as 100 sets can be included for a given headrig. With these instructions, you can specify different processing procedures for different species, grades, and/or sizes of raw material. To illustrate the use of this form, Appendix C shows the filled out forms needed to set up the processing procedure discussed for the band headrig in section 2.3 (Processing and Product Considerations). I should point out that when there is more than one set of sawing instructions and a given species, grade, and/or size of raw material does not fit the criteria for any of them, the first set of sawing instructions will be used on that given raw material. A discussion of the information required on this form follows:

- **HEADRIG ORDER NO.**—The order number of the headrig for which the sawing instructions apply. Note that this is not the equipment number.
- **INSTRUCTION SET NO.**—The sequential number of the instruction set. There can be as many as 100 different sets for a given headrig.
- **SAWING PATTERN CONTROL**—This section is used to designate the species, grade, and/or size raw material to be processed by the specified sawing pattern.
- **SAW CODE**—The code designations for the desired sawing pattern. Appendix D shows diagrams of the available sawing patterns by code. The codes by headrig type are:

Band and circular headrigs:

- 1—Saw around (all).
- 2—Saw around to timber.
- 3—Saw around to cant for resaw.
- 4—Slab around to timber (slabs to chipper).
- 5—Slab around to timber (slabs to resaw).
- 6—Slab around to cant for resaw (slabs to chipper).
- 7—Slab around to 2-sided cant for resaw (slabs to chipper).
- 8—Slab around to cant for resaw (slabs to resaw).
- 9—Slab around to 2-sided cant for resaw (slabs to resaw).
- 10—Live saw.

- 12—Saw around to 2-sided cant for resaw.
- 13—Same as code 3 but with even number pieces in cant.
- 14—Same as code 6 but with even number pieces in cant.
- 15—Same as code 8 but with even number pieces in cant.
- 16—Saw around to 3-sided cant for resaw.
- 17—Slab around to 3-sided cant for resaw (slabs to chipper).
- 18—Slab around to 3-sided cant for resaw (slabs to resaw).

Scragg Headrig:

- 4—Two passes to timber (slabs to chipper).
- 5—Two passes to timber (slabs to resaw).
- 6—Two passes to cant for resaw (slabs to chipper).
- 7—One pass to 2-sided cant for resaw (slabs to chipper).
- 8—Two passes to cant for resaw (slabs to resaw).
- 9—One pass to 2-sided cant for resaw (slabs to resaw).
- 14—Same as code 6 but with even number pieces in cant.
- 15—Same as code 8 but with even number pieces in cant.

Gang Headrig:

- 11—Gang saw.

- SP CODE—The species code for raw material to be processed by the set of sawing instructions if species is to be used as a decision criteria.
- GR—The grade of raw material to be processed by the set of sawing instructions if grade is to be used as a decision criteria.
- UPPER DIAM.—The upper diameter limit, in inches, (small end) of raw material to be processed by the set of sawing instructions if it is to be used as a decision criteria.
- LOWER DIAM.—The lower diameter limit, in inches, (small end) of raw material to be processed by the set of sawing instructions if it is to be used as a decision criteria.
- UPPER LGTH—The upper length limit, in feet, of the raw material to be processed by the set of sawing instructions if it is to be used as a decision criteria.
- LOWER LGTH—The lower length limit, in feet, of the raw material to be processed by the set of sawing instructions if it is to be used as a decision criteria.

- CRI. CODE—Additional criteria codes used in combination with the above decision criteria. Enter a code here if the set of sawing instructions to be used on a given species, grade, and/or size of log or bolt is to be picked from two or more sets of sawing instructions. These codes indicate whether the set of sawing instructions is to be picked on a sequential or percentage basis. For example, let us say that all Grade 3 red oak logs less than 16 inches in diameter are to be processed by three different sets of sawing instructions on a sequential basis. The first log fitting this description will be processed by the first set, the second log by the second set, the third log by the third set, the fourth log by the first set, and so on. On a percentage basis, the set of sawing instructions will be chosen according to the percentages entered for the different sets. The codes are:

- 1—Enter when raw material fitting a given set of decision criteria is to be processed by two or more different sets of sawing instructions on a sequential basis.
- 2—Enter when raw material fitting a given set of decision criteria is to be processed by two or more different sets of sawing instructions on a percentage basis.

- PERCENT—The percentage of the raw material (for a given set of decision criteria) that is to be processed by a given set of sawing instructions when a CRI. CODE of 2 has been used.
- SAWING DIMENSIONS—The following information provides the saw kerfs and product sizes for processing the log and/or bolts:
- BOARD MIN. LGTH—The minimum board length, in feet, allowed when processing a log or bolt.
- SAW KERF—One or more of the following saw kerfs to the thousandths of an inch are required.
- HDRIG—A headrig saw kerf is always required.
- CANT—If cants are to be resawed, a resaw saw kerf is required. This resaw can be either a gang, centerline, or linebar.
- SLAB—If slabs are to be resawed, the saw kerf for the slab resaw is required.
- BOARD THICKNESS—The following information sets the board thicknesses:
- ROUGH CANT—If cants are to be produced and sent to a resaw, enter the rough thickness, in inches, of resulting boards. Or, if timbers are to be produced from the centers of the log, enter their width. For example, if 6- by 8-inch timbers are to be produced, enter 8.000. But if neither cants nor timbers are to be produced from the centers of the logs or bolts, enter 0.000.

- ROUGH SLAB—If slabs are to be produced and sent to a resaw, enter the rough thickness, in inches, of the resulting boards. If the logs or bolts are to be sawed around to a cant or timber, enter the rough thickness of the resulting side boards. Or, if the logs or bolts are to be sawed around (all) or live sawn, enter the rough thickness of the resulting boards.
- NOMINAL CANT—Enter the nominal thickness, in inches, for the rough thickness entered under “ROUGH CANT.”
- NOMINAL SLAB—Enter the nominal thickness, in inches, for the rough thickness entered under “ROUGH SLAB.”
- MAXIMUM CANT WIDTH—Enter the maximum width, in inches, of cants to be sent to a resaw. This can also be used to limit the size of a cant that is to be produced and split on the headrig. An example of this would be an 8- by 12-inch (plus saw kerf) cant that is produced and split on the headrig into two 6- by 8-inch cants. In this situation, the maximum cant width would be 12 inches plus the saw kerf. If there are no restrictions on cant widths, this value will be “0.”
- ALLOWABLE BOARD WIDTH—Enter up to 30 board widths, in inches, that will be allowed in the processing of logs or bolts. Enter them in increasing order of widths.
- ALLOWABLE CANT THICK.—Enter up to 30 cant thicknesses, in inches, that will be allowed in the processing of logs or bolts. If timbers are to be produced, these would be the allowable thicknesses of the timbers. Enter them in increasing order of thickness.

4.7 Form No. 21—Conveyor and buffer information. In the discussion of this form, the terms conveyor and buffer are used. Conveyor is a straight-line conveyor from a machine center or transfer station feeding directly into the following machine center or buffer. Buffer is a cross transfer chain located just ahead of a machine center that is used to store pieces to be processed by the machine.

Most of the information required on this form comes directly from a sawmill layout diagram. But, when several machines are sending material to one machine, the task of filling out this form can be difficult. Consider the situation where machine No. 12 is fed by two buffers. One of these buffers receives material from both machine No. 5 and machine No. 6. And, the other buffer receives material from both machine No. 8 and machine No. 10. An example of this situation is shown on Form No. 21 in Appendix B. I suggest you work through this example as you consider the inputs that follow.

- MACHINE NO.—Enter the machine number of the machine receiving material. Since raw material input stations such as forklifts or cranes do not receive material, their number will not be entered here.

- **NUMBER BUFF. OR CONV. FEEDING**—Enter the number of buffers feeding the machine designated under “MACHINE NO.” If no buffers feed the machine, enter the number of conveyors feeding it. There is no limit to the number of conveyors or buffers that can be used other than the physical limitations of an actual sawmill layout.
- **NUMBER MACHINE TO EACH**—Enter the number of different machines feeding each conveyor or buffer.
- **SENDING MACHINE NO.**—For each buffer or conveyor feeding the machine, enter the sending machine number.
- **TRANSFER CODE**—For each sending machine, enter the transfer code. The codes are:
 - 1—The sending machine is the only one providing material to the particular buffer of the receiving machine.
 - 2—The sending machine and a go-around conveyor system providing material to the particular buffer of the receiving machine.
 - 3—More than one machine sending material to the particular buffer of the receiving machine.
 - 4—Only a go-around conveyor system providing material to the particular buffer of the receiving machine.
 - 5—The sending machine is the only one providing material to a conveyor feeding the receiving machine.
 - 7—More than one sending machine providing material to a conveyor feeding the receiving machine.
- **BUFFER LENGTH**—Enter the length, in feet, for the particular buffer feeding the receiving machine. If no buffer is used, no entry is required.
- **BUFFER SPEED**—Enter the speed, in feet per minute, for the particular buffer feeding the receiving machine. If no buffer is used, no entry is required.
- **CONVEYOR LENGTH**—Enter the length, in feet, of the conveyor feeding the particular buffer or receiving machine. No entry is required if material is sent from sending machine directly to the receiving machine buffer without the use of a conveyor.
- **CONVEYOR SPEED**—Enter the speed, in feet per minute, of the conveyor feeding the particular buffer or receiving machine. No entry is required if material is sent from sending machine directly to the receiving machine buffer without the use of a conveyor.

4.8 Form No. 22—Criteria for routing material. Use this form to set up the routing of the different types of material through the proposed sawmill. Each line on the form represents a set of routing instructions. A discussion of the required information follows. Much of this information can be taken from the sawmill diagram plus the process and products considerations that should have been set up at the beginning of the design process. As many as 100 separate routing possibilities can be included for a given sawmill design.

- FROM NO.—Enter the machine number of the machine sending the material.
- TO NO.—Enter the machine number of the machine receiving the material.
- TYPE CODE—This code indicates the type of material being routed. The codes are:

- 1—Long-length piece (made up of standard sawlogs).
- 2—Long-length piece (made up of standard sawlogs and/or bolts).
- 3—Standard sawlogs.
- 4—Bolts.
- 5—Unedged boards.
- 6—Edged boards.
- 7—Timbers.
- 8—Cants for resaw.
- 9—Railroad ties.
- 10—Slabs for chipper.
- 11—Chips.
- 12—Special products (headers, half headers, etc.)
- 13—Slabs for resaw.
- 14—Cants (2- and 3-sided) for resaw.

- ROUTE CODE—This code indicates how the material is going to be routed. A given type, species, grade, and/or size of material can be routed to as many as three different machines on a priority basis, alternating basis, or percentage basis. If a given piece of material is to be sent to two machines on a priority basis, this code will indicate the two sets of routing instructions and the priorities will be designated under "PRI." For example see Form No. 22 in Appendix B. As these pieces are produced, they will always be routed according to the first instruction set unless the buffer for the receiving machine is full. Then the second instruction set will be used. As soon as the machine buffer related to the first instruction set is less than or equal to 75 percent full, these pieces will again be routed according to the first instruction set. When given pieces of material are routed to two or three different machines on an alternating basis, a different set of routing instructions will be used each time. And, when given pieces of material are routed on a percentage basis, the instruction sets are picked according to the percentages that have been assigned. The codes for this procedure are:

- **LN. CODE**—The length codes are:

- 1—Enter if only indicated length is to be routed.
- 2—Enter if only lengths less than the indicated length are to be routed.
- 3—Enter if only lengths equal to or greater than the indicated length are to be routed.

- **PRI.**—If a “ROUTE CODE” of 1 has been entered for as many as three different routing possibilities (for the same routing criteria), enter the routing priority for each possibility. These routing priorities will be entered as 1 through 2 or through 3 depending on the number of possibilities. For an example, see lines 1 and 2 on Form No. 22 in Appendix B.
- **ALT.**—If a “ROUTE CODE” of 2 has been entered for up to three different routing possibilities for the same routing criteria, enter an alternate number 1 for each possibility in the set. If there is another set of routing possibilities for other routing criteria, enter an alternate number 2. In other words, a different alternate number must be used for each set of routing possibilities. For an example, see lines 3 and 4 on Form No. 22 in Appendix B.
- **PERCENT**—If a “ROUTE CODE” of 3 has been entered for as many as three different routing possibilities (for the same routing criteria), enter the corresponding percentage for each possibility. These percentages must total 100 for the different possibilities. For an example, see lines 5 and 6 on Form No. 22 in Appendix B.

Creating Raw Material Data Files

If actual piece data is to be used as raw material input and this information has been entered on forms (Form No. 1), the information from these forms must be input to your CMS file. The first data set is designated as “MAT1 DATA A1.” If there is more than one data set, the second one is designated as “MAT2 DATA A1” and so on. These file designations must be used to correspond to the JCL that has been set up for the DESIGN program.

- 0—Enter if no criteria other than material type are to be used or if only species, grade, and/or size along with material type are to be used to route the piece. This code must be used when routing 2-sided and 3-sided cants for resaw (type code 14) and slabs for resaw (type code 13). This material cannot be routed on a priority, alternating, or percentage basis.
- 1—Enter if pieces are also to be routed on a priority basis (see lines 1 and 2 on Form No. 22 in Appendix B).
- 2—Enter if pieces are also to be routed on an alternating basis (see lines 3 and 4 on Form No. 22 in Appendix B).
- 3—Enter if pieces are also to be routed on a percentage basis (see lines 5 and 6 on Form No. 22 in Appendix B).

- **GRADE**—Enter grade of piece if grade is to be used as a routing criteria.
- **SPECIES CODE**—Enter species of the piece if species is to be used as a routing criteria.
- **WIDTH**—Enter width (small-end diameter for logs or bolts), in inches, if width is to be used as a routing criteria.
- **WD. CODE**—The width codes are:
 - 1—Enter if only indicated width is to be routed.
 - 2—Enter if only widths less than the indicated width are to be routed.
 - 3—Enter if only widths equal to or greater than the indicated widths are to be routed.
- **THICKNESS**—Enter thickness, in inches, if thickness is to be used as a routing criteria.
- **TH. CODE**—The thickness codes are:
 - 1—Enter if only indicated thickness is to be routed.
 - 2—Enter if only thicknesses less than the indicated thickness are to be routed.
 - 3—Enter if only thicknesses equal to or greater than the indicated thickness are to be routed.
- **LENGTH**—Enter length, in feet, if length is to be used as a routing criteria.

6. Running DESIGN Program

Once the sawmill layout has been drawn, the data forms filled out, and the raw material data files created (if needed), you are ready to run the DESIGN program. This is done by entering "DESIGN" at the CMS terminal. Through the terminal you will be asked questions and prompted for the answers. The answers to most of the questions will come directly from the data forms. When prompted for the answers, the data fields will be indicated on the screen. These fields correspond to the fields used on the data forms. When entering data into the fields, a ":" or a "_" (that is, not to contain a letter or number) indicates that you must space over

one space before entering the required information. For example, “: : : _ 1 . 2 5” indicates that you space over four spaces before entering the 1.25. Also, when entering a number containing a decimal point, the decimal point must also be entered. And, if a value for a given piece of information is to be “0”, it is not necessary to enter anything in that field.

Once a given set of data has been punched in at the CMS terminal and the return key pressed, you have the opportunity to check the information on the screen to see if it is correct and in the right fields. If it is correct, you press the space bar and then press the return key again. At this point you will be asked the next question. However, if the information is not correct or it is in the wrong field, press “E” and then press the return key. At this point you will be asked the same question again and prompted for the correct information.

When you have answered all the questions, the DESIGN program produces both the “MILL DATA A1” file and the “GASP DATA A1” file required by the SIMU program to simulate the operation of the proposed sawmill system.

Running SIMU ogram

To run the SIMU program, enter “SIMU” at the CMS terminal. The operation of the sawmill system is then simulated and the resulting output sent back to the user’s CMS reader file. The user can either look at the output on the terminal screen or have it sent to the printer. Since the output is rather long, I suggest that it be sent to the printer.

Modifying a wmill System

Once a sawmill system has been set up and simulated, you may wish to modify it to determine what effect the change will have on the operation of the system. These modifications can include anything in the system including: (1) raw material inputs, (2) adding or deleting machines, (3) machine data, (4) conveyor and/or surge deck systems, (5) processing instructions, and (6) routing instructions. After determining exactly what you wish to change, run the DESIGN program again. However, first if you wish to retain the original “MILL DATA A1” file for possible future use, make a copy file of this information under another name. You might use a designation such as “MILL1 DATA A1”. A copy file is necessary because after rerunning the DESIGN program, the original “MILL DATA A1” file will be changed to reflect the modifications. When ready to make the modifications, run the DESIGN program. You will be asked if this is a new design. After entering “N” for no, you will be asked a series of questions and be prompted for the information needed to make the required modifications. When all of the questions have been answered, the modified “MILL DATA A1” is produced and the old “MILL DATA A1” file is erased. At this point you run the SIMU program again to obtain the output for the simulated operation of the modified sawmill system.

Literature Cited

- Adams, Edward L. **DESIM: A system for designing and simulating hardwood sawmill systems**. Gen. Tech. Rep. NE-89. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1984. 10 p.
- Pritsker, A. Alan B. **The GASP IV simulation language**. New York: John Wiley & Sons; 1974. 451 p.
- Pritsker, A. Alan B. **The GASP IV user's manual**. 2d. ed. W. Lafayette, IN: Pritsker & Associates, Inc.; 1977. 100 p.

Appendix A—IBM System

Instructions for getting the DESIM computer-type information into your user files and setting up the control files for using the system

Setting up DESIM

This section provides the procedures for transferring files from the DESIM computer tape to your CMS files and for setting up the computer control files needed to use the DESIM system.

1.1 Tape to CMS File

The DESIM system is on a 9-track computer tape at a density of 1600 bits per inch. It is in a nonlabeled fixed-block format with a record length of 80 and a block size of 6000. This information consists of three computer programs and two support data files.

To move the programs and data files to your CMS files, the computer tape is first submitted to the computer center tape library. Next, on the CMS terminal, create a file designated "GET CNTL A1" and input the following statements:

```
//BVVVV JOB      WWWWW,XXXXXXX
/*PRIORITY      STANDARD
/*LONGKEY       YYYYYYYY
/*ROUTE PRINT   VM1.ZZZZZZZ
//STEP1 EXEC    PGM=IEBGENER
//SYSPRINT DD   SYSOUT=A
//SYSUT1 DD     DISP=(OLD,KEEP),
//              VOL=SER=DESIM1,
//              UNIT=TAPE,
//              DCB=(RECFM=FB,LRECL=80,BLKSIZE=6000,DEN=3),
//              LABEL=(1,NL)
//SYSUT2 DD     SYSOUT=B
//SYSIN DD      DUMMY
//
```

In the first statement, "VVVV" is to be replaced with your user's box number, "WWWWW" is to be replaced with your user's account number, and "XXXXXXX" is to be replaced with your name. In the LONGKEY statement, "YYYYYYY" is to be replaced with your password. In the ROUTE PRINT statement, "ZZZZZZZ" is to be replaced with your CMS user's identification (ID) name.

Once the above statements have been input to "GET CNTL A1", the file must be saved. It will be modified and used several times for moving the programs and data files from the DESIM tape to your CMS file. The procedure for doing this is:

- **FORMS PROGRAM**—Through the CMS terminal, submit the “GET CNTL A1” file to the multiple virtual storage (MVS) operating system of the mainframe computer. As soon as the run has been completed, the FORMS program will be passed to your CMS reader file. Move the program to your CMS file by reading it from the reader file with the designation “FORMS FORTRAN A1”.
- **DESIGN PROGRAM**—Modify the “GET CNTL A1” file by changing “LABEL = (1,NL)” to “LABEL = (2,NL)”. Submit “GET CNTL A1” to the MVS operating system. The DESIGN program will be returned to the reader file. Move the program to your CMS file with the designation “DESIGN FORTRAN A1”.
- **SIMULATION PROGRAM**—Modify the “GET CNTL A1” file by changing “LABEL = (2,NL)” to “LABEL = (3,NL)”. Submit “GET CNTL A1” to the MVS operating system. The SIMU program will be returned to the reader file. Move the program to your CMS file with the designation “SIMU FORTRAN A1”.
- **EQUIPMENT DATA FILE**—Modify the “GET CNTL A1” file by changing “LABEL = (3,NL)” to “LABEL = (4,NL)”. Submit “GET CNTL A1” to the MVS operating system. The data file will be returned to the reader file. Move the data file to your CMS file with the designation “EQ DATA A1”.
- **LUMBER GRADE DATA FILE**—Modify the “GET CNTL A1” file by changing “LABEL = (4,NL)” to “LABEL = (5,NL)”. Submit “GET CNTL A1” to the MVS operating system. The data file will be returned to the reader file. Move the data file to your CMS file with the designation “LGR DATA A1”.

At this point the “GET CNTL A1” file can be erased. You now have three computer programs and two data files in your CMS file designated as follows:

FORMS FORTRAN A1

DESIGN FORTRAN A1

SIMU FORTRAN A1

EQ DATA A1

LGR DATA A1

1.2 CMS EXEC Files

To run the three DESIM computer programs, CMS EXEC files and support JCL files must be generated. The EXEC files execute the CMS command procedure necessary for running the programs. The JCL files provide the required job control statements when the computer programs are sent to the MVS system for processing. The EXEC files and support JCL files for each DESIM program are listed below:

- FORMS PROGRAM—For this program, an EXEC file and three JCL files must be generated. They are:

FORMS EXEC A1 (file designation)

```
&CØNTRØL ØFF
STACKSPL PU
&READ VARS &PU1 &PU2 &PU3 &PU4 &PU5
CP SP PUN CLASS J CØNT TØ SYSTEM
PUNCH FØRMS CNTL1 A1 (NØH
PUNALL //FØRT.SYSIN_ DD_*
PUNCH FØRMS FØRTRAN A1 (NØH
PUNCH FØRMS CNTL2 A1 (NØH
PUNCH END CNTL A1 (NØH
CP SP PUN CLOSØ
CP SP PUN &PU1 &PU2 &PU3 &PU4 &PU5
CP QUERY PUNCH ALL
&EXIT
```

FORMS CNTL1 A1 (file designation)

```
//BVVVV JØB          WWWWW,XXXXXXX,TIME = 1,REGIØN = 150K
/*PRIØRITY          STANDARD
/*LØNGKEY           YYYYYYYY
/*JØBPARM           LINES = 50
/*RØUTE PRINT       VM1.ZZZZZZZ
//STEP1 EXEC        FTG1CLG,REGIØN = 150K,TIME = 1
//FØRT.SYSLIN DD    UNIT + SYSDA,SPACE = (CYL,(5,5))
```

FORMS CNTL2 A1 (file designation)

```
//GØ.FT06F001 DD    SYSØUT = (A,,F)
//GØ.FT07F001 DD    SYSØUT = (B,,G)
//GØ.FT08F001 DD    DUMMY
//GØ.SYSIN DD        *
```

END CNTL A1 (file designation)

```
/*
//
```

After the above files have been generated and saved in your CMS file, the FORMS program can be run by simply entering "FORMS" at the CMS terminal. The EXEC program then submits the FORMS program and required JCL statements to the MVS system for running. Upon completion of the run, the output (data forms) is returned to your CMS reader file and must then be sent to a printer.

- DESIGN PROGRAM—This program requires only an EXEC file. No JCL files are required because the program is not sent to the MVS system. It is run on the CMS system. The required EXEC file is:

DESIGN EXEC A1 (file designation)

FØRTGI DESIGN

FI 03 DISK MILL DATA A1 (RECFM F LRECL 80 BLKSIZE 80)

FI 04 DISK EQ DATA A1 (RECFM F LRECL 80 BLKSIZE 80)

FI 05 TERM

FI 06 TERM

FI 09 DISK MIL2 DATA A1 (RECFM F LRECL 80 BLKSIZE 80)

FI 11 DISK MAT1 DATA A1 (RECFM F LRECL 80 BLKSIZE 80)

FI 12 DISK MAT2 DATA A1 (RECFM F LRECL 80 BLKSIZE 80)

FI 13 DISK MAT3 DATA A1 (RECFM F LRECL 80 BLKSIZE 80)

FI 14 DISK MAT4 DATA A1 (RECFM F LRECL 80 BLKSIZE 80)

FI 15 DISK MAT5 DATA A1 (RECFM F LRECL 80 BLKSIZE 80)

FI 16 DISK GAS DATA A1 (RECFM F LRECL 80 BLKSIZE 80)

GLØBAL TXTLIB FØRTXLIB

LØAD DESIGN (CLEAR

START

EXSERV STATE MILL DATA A1

&IF &RETCØDE NE 0 &GØTØ -LABL

ERASE MILL DATA A1

-LABL

RENAME MIL2 DATA A1 MILL DATA A1

EXSERV STATE GASP DATA A1

&IF &RETCØDE NE 0 &GØTØ -LABE

ERASE GAS3 DATA A1

-LABE

RENAME GAS DATA A1 GASP DATA A1

ERASE DESIGN LISTING A1

ERASE DESIGN TEXT A1

After the above EXEC file has been generated and saved in your CMS file, the DESIGN program can be run by simply entering "DESIGN" at the CMS terminal. The EXEC file starts the running of the DESIGN program making available to it: (1) the old "MILL DATA A1" file if it exists, (2) the "EQ DATA A1" file, and (3) up to five raw material data files. The EXEC file then provides for the generation of a new mill data file (MIL2 DATA A1), erases the old mill data file (MILL DATA A1), and renames "MIL2 DATA A1" to "MILL DATA A1". The EXEC file also provides for the generation of the "GASP DATA A1" file required by the SIMU program.

- SIMU PROGRAM—For this program, an EXEC file and two JCL files must be generated. They are:

SIMU EXEC A1 (file designation)

```
&CØNTRØL ØFF
STACKSPL PU
&READ VARS &PU1 &PU2 &PU3 &PU4 &PU5 &PU6 &PU7 &PU8
CP SP PUN CLASS J CØNT TØ SYSTEM
PUNCH SIMU CNTL1 A1 (NØH
PUNALL //FØRT.SYSIN_ DD_*
PUNCH SIMU FØRTRAN A1 (NØH
PUNCH SIMU CNTL2 A1 (NØH
PUNCH GASP DATA A1 (NØH
PUNCH MILL DATA A1 (NØH
PUNCH LGR DATA A1 (NØH
PUNCH END CNTL A1 (NØH
CP SP PUN CLØSE
CP SP PUN &PU1 &PU2 &PU3 &PU4 &PU5 &PU6 &PU7 &PU8
CP QUERY PUNCH ALL
&EXIT
```

SIMU CNTL1 A1 (file designation)

```
//BVVVV JØB WWWWW,XXXXXXX,TIME=5,REGIØN=1500K
/*LØNGKEY YYYYYYYY
/*PRIØRITY STANDARD
/*JØBPARM LINES=50
/*RØUTE PRINT VM1.ZZZZZZZ
//STEP1 EXEC FTG1CLG,LIB='VPI.GASP4.FIXED.FØRMAT',
REGION=1500K,TIME=5
//FØRT.SYSLIN DD UNIT=SYSDA,SPACE=(CYL,(5,5))
```

SIMU CNTL2 A1 (file designation)

```
/*
//GØ.FT06F001 DD SYSØUT=(A,,F)
//GØ.FT07F001 DD SYSØUT=(B,,G)
//GØ.FT08F001 DD DUMMY
//GØ.SYSIN DD *
```

After the above files have been generated and saved in your CMS file, the SIMU program can be run by simply entering "SIMU" at the CMS terminal. The EXEC file then submits the SIMU program, the necessary JCL statements, and the required data files to the MVS operating system. The output is then returned to your CMS reader file.

Appendix B—DESIM Data Forms

FORM NO. 1 (_ _ OF _ _)

RAW MATERIAL ACTUAL PIFCE DATA

DATA SET NO. -
MATERIAL TYPE CODE -

PIECE NUMBER	SPECIES GR CODE	SMALL DIAM.	LARGE DIAM.	LENGTH	CO
-----------------	--------------------	----------------	----------------	--------	----

[illegible]

SPECIES :

CODE NO. -

PERCENT -

LOG TAPER / FOOT -

PERCENT OF LOG GRADE 1 -

PERCENT OF LOGS BY DIAMETER CLASS :

8	9	10	11	12	13	14	15	16	17
18	19	20	21	22	23	24			

PERCENT OF LOGS BY LENGTH CLASS :

8	9	10	11	12	13	14	15	16

PERCENT OF LOG GRADE 2 -

PERCENT OF LOGS BY DIAMETER CLASS :

8	9	10	11	12	13	14	15	16	17
18	19	20	21	22	23	24			

PERCENT OF LOGS BY LENGTH CLASS :

8	9	10	11	12	13	14	15	16

PERCENT OF LOG GRADE 3 -

PERCENT OF LOGS BY DIAMETER CLASS :

8	9	10	11	12	13	14	15	16	17
18	19	20	21	22	23	24			

PERCENT OF LOGS BY LENGTH CLASS :

8	9	10	11	12	13	14	15	16

PERCENT OF LOG GRADE 4 -

PERCENT OF LOGS BY DIAMETER CLASS :

8	9	10	11	12	13	14	15	16	17
18	19	20	21	22	23	24			

PERCENT OF LOGS BY LENGTH CLASS :

8	9	10	11	12	13	14	15	16

BOLT SPECIES AND SIZE DISTRIBUTION

DATA SET NO. -

SPECIES :

CODE NO. - -

PERCENT - - -

BOLT TAPER / FOOT - - -

PERCENT OF BOLTS BY DIAMETER CLASS :

4	5	6	7	8	9	10	11	12	13
::	-	-	-	-	-	-	-	-	-
14	15	16	17	18	19	20			
::	-	-	-	-	-	-	-	-	-

PERCENT OF BOLTS BY LENGTH CLASS :

4	5	6	7	8	9	10	11	12
::	-	-	-	-	-	-	-	-

SPECIES :

CODE NO. - -

PERCENT - - -

BOLT TAPER / FOOT - - -

PERCENT OF BOLTS BY DIAMETER CLASS :

4	5	6	7	8	9	10	11	12	13
::	-	-	-	-	-	-	-	-	-
14	15	16	17	18	19	20			
::	-	-	-	-	-	-	-	-	-

PERCENT OF BOLTS BY LENGTH CLASS :

4	5	6	7	8	9	10	11	12
::	-	-	-	-	-	-	-	-

SPECIES :

CODE NO. - -

PERCENT - - -

BOLT TAPER / FOOT - - -

PERCENT OF BOLTS BY DIAMETER CLASS :

4	5	6	7	8	9	10	11	12	13
::	-	-	-	-	-	-	-	-	-
14	15	16	17	18	19	20			
::	-	-	-	-	-	-	-	-	-

PERCENT OF BOLTS BY LENGTH CLASS :

4	5	6	7	8	9	10	11	12
::	-	-	-	-	-	-	-	-

SPECIES :

CODE NO. - -

PERCENT - - -

BOLT TAPER / FOOT - - -

PERCENT OF BOLTS BY DIAMETER CLASS :

4	5	6	7	8	9	10	11	12	13
::	-	-	-	-	-	-	-	-	-
14	15	16	17	18	19	20			
::	-	-	-	-	-	-	-	-	-

PERCENT OF BOLTS BY LENGTH CLASS :

4	5	6	7	8	9	10	11	12
::	-	-	-	-	-	-	-	-

MILL DESIGN

FOR THIS MILL DESIGN ENTER :

PROJECT NAME	PROJECT NO.	NUMBER RUNS	RUN TIME	PURGE TIME
- - - - -	: : :	- - - - -	- - - - -	- - - - -

DO YOU WANT AN UNBLOCKED MILL RUN ? (N / Y) -

ACTUAL LOG AND/OR BOLT DATA

MATERIAL TYPE CODE :
1 = LONG LENGTH (LOGS)
2 = LONG LENGTH (LOGS AND/OR BOLTS)
3 = LOGS
4 = BOLTS

DATA SET NO. -	MATERIAL TYPE CODE -
DATA SET NO. -	MATERIAL TYPE CODE -
DATA SET NO. -	MATERIAL TYPE CODE -
DATA SET NO. -	MATERIAL TYPE CODE -
DATA SET NO. -	MATERIAL TYPE CODE -

MACHINE DATA (RAW MATERIAL INPUT STATION - FORKLIFT OR CRANE)

MACHINE NO. _ _
 MACHINE NAME _ _ _ _ _
 MACHINE CODE (1 OR 2) _ _
 RAW MATERIAL CODE _
 RAW MATERIAL DATA SET _

PROCESSING TIMES AND RATES :
 TIME CODE _

SPECIES CODE _ _
 PROCESSING TIME (MINUTES) _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****

MEAN	MIN.	MAX.	SD
------	------	------	----

DOWN TIME : : : :
-------------------	---------	---------	---------

PERCENT DOWN: _ _ . _ _ _

SPECIES CODE _ _
 PROCESSING TIME (MINUTES) _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****

MEAN	MIN.	MAX.	SD
------	------	------	----

DOWN TIME : : : :
-------------------	---------	---------	---------

PERCENT DOWN: _ _ . _ _ _

SPECIES CODE _ _
 PROCESSING TIME (MINUTES) _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****

MEAN	MIN.	MAX.	SD
------	------	------	----

DOWN TIME : : : :
-------------------	---------	---------	---------

PERCENT DOWN: _ _ . _ _ _

SPECIES CODE _ _
 PROCESSING TIME (MINUTES) _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****

MEAN	MIN.	MAX.	SD
------	------	------	----

DOWN TIME : : : :
-------------------	---------	---------	---------

PERCENT DOWN: _ _ . _ _ _

MACHINE DATA (BUCK SAW)

MACHINE NO. - -
 MACHINE NAME
 MACHINE CODE 3

PROCESSING TIMES AND RATES :
 TIME CODE -

SPECIES CODE - -
 FEED RATE (INCHES / MIN.) : - - - . - -

PROCESSING TIME DISTRIBUTION :
 ***** LOGNORMAL DISTRIBUTION *****
 MEAN MIN. MAX. SD
 LOAD TIME : - - . - - : - - . - - : - - . - - : - - . - -
 DOWN TIME : - - . - - : - - . - - : - - . - - : - - . - -
 PERCENT DOWN : - - . - -

SPECIES CODE - -
 FEED RATE (INCHES / MIN.) : - - - . - -

PROCESSING TIME DISTRIBUTION :
 ***** LOGNORMAL DISTRIBUTION *****
 MEAN MIN. MAX. SD
 LOAD TIME : - - . - - : - - . - - : - - . - - : - - . - -
 DOWN TIME : - - . - - : - - . - - : - - . - - : - - . - -
 PERCENT DOWN : - - . - -

SPECIES CODE - -
 FEED RATE (INCHES / MIN.) : - - - . - -

PROCESSING TIME DISTRIBUTION :
 ***** LOGNORMAL DISTRIBUTION *****
 MEAN MIN. MAX. SD
 LOAD TIME : - - . - - : - - . - - : - - . - - : - - . - -
 DOWN TIME : - - . - - : - - . - - : - - . - - : - - . - -
 PERCENT DOWN : - - . - -

SPECIES CODE - -
 FEED RATE (INCHES / MIN.) : - - - . - -

PROCESSING TIME DISTRIBUTION :
 ***** LOGNORMAL DISTRIBUTION *****
 MEAN MIN. MAX. SD
 LOAD TIME : - - . - - : - - . - - : - - . - - : - - . - -
 DOWN TIME : - - . - - : - - . - - : - - . - - : - - . - -
 PERCENT DOWN : - - . - -

MACHINE DATA (DEBARKER)

MACHINE NO. _ _
 MACHINE NAME _ _ _ _ _
 MACHINE CODE (4 OR 5) _ _

PROCESSING TIMES AND RATES :
 TIME CODE _

SPECIES CODE _ _
 PROC. TIME (MIN./10 SQ. FT. FOR MACHINE CODE 4) : _ _ _ . _ _
 OR
 FEED RATE (FT./MIN. FOR MACHINE CODE 5) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

	***** LOGNORMAL DISTRIBUTION *****
	MEAN MIN. MAX. SD
LOAD TIME :	_ . _ _ _ : _ . _ _ _ : _ . _ _ _ : _ . _ _ _
DOWN TIME :	_ . _ _ _ : _ . _ _ _ : _ . _ _ _ : _ . _ _ _
PERCENT DOWN :	_ . _ _ _

SPECIES CODE _ _
 PROC. TIME (MIN./10 SQ. FT. FOR MACHINE CODE 4) : _ _ _ . _ _
 OR
 FEED RATE (FT./MIN. FOR MACHINE CODE 5) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

	***** LOGNORMAL DISTRIBUTION *****
	MEAN MIN. MAX. SD
LOAD TIME :	_ . _ _ _ : _ . _ _ _ : _ . _ _ _ : _ . _ _ _
DOWN TIME :	_ . _ _ _ : _ . _ _ _ : _ . _ _ _ : _ . _ _ _
PERCENT DOWN :	_ . _ _ _

SPECIES CODE _ _
 PROC. TIME (MIN./10 SQ. FT. FOR MACHINE CODE 4) : _ _ _ . _ _
 OR
 FEED RATE (FT./MIN. FOR MACHINE CODE 5) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

	***** LOGNORMAL DISTRIBUTION *****
	MEAN MIN. MAX. SD
LOAD TIME :	_ . _ _ _ : _ . _ _ _ : _ . _ _ _ : _ . _ _ _
DOWN TIME :	_ . _ _ _ : _ . _ _ _ : _ . _ _ _ : _ . _ _ _
PERCENT DOWN :	_ . _ _ _

MACHINE DATA (BAND OR CIRCULAR HEADRIG)

FORM NO. 8 (_ _ OF _ _)

MACHINE NO. _ _
MACHINE NAME _ _ _ _ _
MACHINE CODE (6,7,8,OR 9) _ _
HEADRIG ORDER NO. _

PROCESSING TIMES AND RATES :
TIME CODE _

SPECIES CODE _ _
PROCESSING TIME DISTRIBUTION :

	***** LOGNORMAL DISTRIBUTION *****
	MEAN MIN. MAX. SD
LOAD TIME :	_ . _ _ : _ . _ _ : _ . _ _ : _ . _ _
TURN TIME :	_ . _ _ : _ . _ _ : _ . _ _ : _ . _ _
SLAB TIME :	_ . _ _ : _ . _ _ : _ . _ _ : _ . _ _
LINE TIME :	_ . _ _ : _ . _ _ : _ . _ _ : _ . _ _
DOWN TIME :	_ . _ _ : _ . _ _ : _ . _ _ : _ . _ _

PERCENT DOWN: _ . _ _ _

SPECIES CODE _ _
PROCESSING TIME DISTRIBUTION :

	***** LOGNORMAL DISTRIBUTION *****
	MEAN MIN. MAX. SD
LOAD TIME :	_ . _ _ : _ . _ _ : _ . _ _ : _ . _ _
TURN TIME :	_ . _ _ : _ . _ _ : _ . _ _ : _ . _ _
SLAB TIME :	_ . _ _ : _ . _ _ : _ . _ _ : _ . _ _
LINE TIME :	_ . _ _ : _ . _ _ : _ . _ _ : _ . _ _
DOWN TIME :	_ . _ _ : _ . _ _ : _ . _ _ : _ . _ _

PERCENT DOWN: _ . _ _ _

SPECIES CODE _ _
PROCESSING TIME DISTRIBUTION :

	***** LOGNORMAL DISTRIBUTION *****
	MEAN MIN. MAX. SD
LOAD TIME :	_ . _ _ : _ . _ _ : _ . _ _ : _ . _ _
TURN TIME :	_ . _ _ : _ . _ _ : _ . _ _ : _ . _ _
SLAB TIME :	_ . _ _ : _ . _ _ : _ . _ _ : _ . _ _
LINE TIME :	_ . _ _ : _ . _ _ : _ . _ _ : _ . _ _
DOWN TIME :	_ . _ _ : _ . _ _ : _ . _ _ : _ . _ _

PERCENT DOWN: _ . _ _ _

MACHINE DATA (SCRAGG HEADRIG)

MACHINE NO. _ _
 MACHINE NAME _ _ _ _ _
 MACHINE CODE 10
 HEADRIG ORDER NO. _

PROCESSING TIMES AND RATES :
 TIME CODE _

SPECIES CODE _ _
 FEED RATE (FT./MIN.) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****

	MEAN	MIN.	MAX.	SD
LOAD TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
DOWN TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _

PERCENT DOWN: _ _ . _ _ _

SPECIES CODE _ _
 FEED RATE (FT./MIN.) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****

	MEAN	MIN.	MAX.	SD
LOAD TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
DOWN TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _

PERCENT DOWN: _ _ . _ _ _

SPECIES CODE _ _
 FEED RATE (FT./MIN.) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****

	MEAN	MIN.	MAX.	SD
LOAD TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
DOWN TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _

PERCENT DOWN: _ _ . _ _ _

SPECIES CODE _ _
 FEED RATE (FT./MIN.) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****

	MEAN	MIN.	MAX.	SD
LOAD TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
DOWN TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _

PERCENT DOWN: _ _ . _ _ _

MACHINE DATA (GANG HEADRIG)

MACHINE NO. _ _
 MACHINE NAME
 MACHINE CODE 11
 HEADRIG ORDER NO. _

PROCESSING TIMES AND RATES :
 TIME CODE _

SPECIES CODE _ _
 FEED RATE (FT./MIN.) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :
 ***** LOGNORMAL DISTRIBUTION *****

	MEAN	MIN.	MAX.	SD
LOAD TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
DOWN TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _

 PERCENT DOWN: _ _ . _ _ _

SPECIES CODE _ _
 FEED RATE (FT./MIN.) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :
 ***** LOGNORMAL DISTRIBUTION *****

	MEAN	MIN.	MAX.	SD
LOAD TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
DOWN TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _

 PERCENT DOWN: _ _ . _ _ _

SPECIES CODE _ _
 FEED RATE (FT./MIN.) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :
 ***** LOGNORMAL DISTRIBUTION *****

	MEAN	MIN.	MAX.	SD
LOAD TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
DOWN TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _

 PERCENT DOWN: _ _ . _ _ _

SPECIES CODE _ _
 FEED RATE (FT./MIN.) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :
 ***** LOGNORMAL DISTRIBUTION *****

	MEAN	MIN.	MAX.	SD
LOAD TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
DOWN TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _

 PERCENT DOWN: _ _ . _ _ _

MACHINE DATA (EDGER OR COMBINATION EDGER)

MACHINE NO. _ _

MACHINE NAME _ _ _ _ _

MACHINE CODE (12 OR 13) _ _

PROCESSING TIMES AND RATES :

TIME CODE _

SPECIES CODE _ _

FEED RATE (FT./MIN.) :

BOARD CANT

_ _ _ . _ _ : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****

MEAN MIN. MAX. SD

BOARD LOAD TIME : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _

CANT LOAD TIME : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _

DOWN TIME : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _

PERCENT DOWN : _ _ . _ _ _

SPECIES CODE _ _

FEED RATE (FT./MIN.) :

BOARD CANT

_ _ _ . _ _ : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****

MEAN MIN. MAX. SD

BOARD LOAD TIME : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _

CANT LOAD TIME : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _

DOWN TIME : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _

PERCENT DOWN : _ _ . _ _ _

SPECIES CODE _ _

FEED RATE (FT./MIN.) :

BOARD CANT

_ _ _ . _ _ : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****

MEAN MIN. MAX. SD

BOARD LOAD TIME : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _

CANT LOAD TIME : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _

DOWN TIME : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _

PERCENT DOWN : _ _ . _ _ _

MACHINE DATA (CENTER-LINE RESAW)

FORM NO. 12 (_ _ OF _ _)

MACHINE NO. _ _
 MACHINE NAME _ _ _ _ _ _ _ _ _ _
 MACHINE CODE 14

PROCESSING TIMES AND RATES :
 TIME CODE _

SPECIES CODE _ _
 FEED RATE (FT./MIN.) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****				
	MEAN	MIN.	MAX.	SD
LOAD TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
DOWN TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
PERCENT DOWN:	_ . _ _ _			

SPECIES CODE _ _
 FEED RATE (FT./MIN.) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****				
	MEAN	MIN.	MAX.	SD
LOAD TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
DOWN TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
PERCENT DOWN:	_ . _ _ _			

SPECIES CODE _ _
 FEED RATE (FT./MIN.) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****				
	MEAN	MIN.	MAX.	SD
LOAD TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
DOWN TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
PERCENT DOWN:	_ . _ _ _			

SPECIES CODE _ _
 FEED RATE (FT./MIN.) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****				
	MEAN	MIN.	MAX.	SD
LOAD TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
DOWN TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
PERCENT DOWN:	_ . _ _ _			

MACHINE DATA (LINE-BAR RESAW)

MACHINE NO. _ _
 MACHINE NAME _ _ _ _ _ _ _ _ _ _
 MACHINE CODE 15

PROCESSING TIMES AND RATES :
 TIME CODE _

SPECIES CODE _ _
 FEED RATE (FT./MIN.) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****				
	MEAN	MIN.	MAX.	SD
LOAD TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
DOWN TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
PERCENT DOWN:	_ . _ _ _			

SPECIES CODE _ _
 FEED RATE (FT./MIN.) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****				
	MEAN	MIN.	MAX.	SD
LOAD TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
DOWN TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
PERCENT DOWN:	_ . _ _ _			

SPECIES CODE _ _
 FEED RATE (FT./MIN.) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****				
	MEAN	MIN.	MAX.	SD
LOAD TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
DOWN TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
PERCENT DOWN:	_ . _ _ _			

SPECIES CODE _ _
 FEED RATE (FT./MIN.) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****				
	MEAN	MIN.	MAX.	SD
LOAD TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
DOWN TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _
PERCENT DOWN:	_ . _ _ _			

MACHINE DATA (GANG RESAW)

MACHINE NO. - -
 MACHINE NAME - - - - -
 MACHINE CODE 16

PROCESSING TIMES AND RATES :
 TIME CODE -

SPECIES CODE - -
 FEED RATE (FT./MIN.) : - - - . - -

PROCESSING TIME DISTRIBUTION :
 ***** LOGNORMAL DISTRIBUTION *****
 MEAN MIN. MAX. SD
 LOAD TIME : - - . - - : - - . - - : - - . - - : - - . - -
 DOWN TIME : - - . - - : - - . - - : - - . - - : - - . - -
 PERCENT DOWN : - - . - -

SPECIES CODE - -
 FEED RATE (FT./MIN.) : - - - . - -

PROCESSING TIME DISTRIBUTION :
 ***** LOGNORMAL DISTRIBUTION *****
 MEAN MIN. MAX. SD
 LOAD TIME : - - . - - : - - . - - : - - . - - : - - . - -
 DOWN TIME : - - . - - : - - . - - : - - . - - : - - . - -
 PERCENT DOWN : - - . - -

SPECIES CODE - -
 FEED RATE (FT./MIN.) : - - - . - -

PROCESSING TIME DISTRIBUTION :
 ***** LOGNORMAL DISTRIBUTION *****
 MEAN MIN. MAX. SD
 LOAD TIME : - - . - - : - - . - - : - - . - - : - - . - -
 DOWN TIME : - - . - - : - - . - - : - - . - - : - - . - -
 PERCENT DOWN : - - . - -

SPECIES CODE - -
 FEED RATE (FT./MIN.) : - - - . - -

PROCESSING TIME DISTRIBUTION :
 ***** LOGNORMAL DISTRIBUTION *****
 MEAN MIN. MAX. SD
 LOAD TIME : - - . - - : - - . - - : - - . - - : - - . - -
 DOWN TIME : - - . - - : - - . - - : - - . - - : - - . - -
 PERCENT DOWN : - - . - -

MACHINE DATA (TRIM SAWS)

MACHINE NO. _ _
MACHINE NAME _ _ _ _ _
MACHINE CODE 17

PROCESSING TIMES AND RATES :
TIME CODE _

SPECIES CODE _ _
PROCESSING TIME (MINUTES) _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :
***** LOGNORMAL DISTRIBUTION *****
MEAN MIN. MAX. SD
DOWN TIME : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _
PERCENT DOWN : _ _ . _ _ _

SPECIES CODE _ _
PROCESSING TIME (MINUTES) _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :
***** LOGNORMAL DISTRIBUTION *****
MEAN MIN. MAX. SD
DOWN TIME : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _
PERCENT DOWN : _ _ . _ _ _

SPECIES CODE _ _
PROCESSING TIME (MINUTES) _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :
***** LOGNORMAL DISTRIBUTION *****
MEAN MIN. MAX. SD
DOWN TIME : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _
PERCENT DOWN : _ _ . _ _ _

SPECIES CODE _ _
PROCESSING TIME (MINUTES) _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :
***** LOGNORMAL DISTRIBUTION *****
MEAN MIN. MAX. SD
DOWN TIME : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _
PERCENT DOWN : _ _ . _ _ _

CHINE DATA (GREEN CHAIN)

ACHINE NO. _ _
 ACHINE NAME _ _ _ _ _
 ACHINE CODE 18

ROCESSING TIMES AND RATES :
 IME CODE _

PECIES CODE _ _
 PROCESSING TIME (MINUTES) _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :
 ***** LOGNORMAL DISTRIBUTION *****
 MEAN MIN. MAX. SD
 DOWN TIME : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _
 PERCENT DOWN : _ _ . _ _ _

PECIES CODE _ _
 PROCESSING TIME (MINUTES) _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :
 ***** LOGNORMAL DISTRIBUTION *****
 MEAN MIN. MAX. SD
 DOWN TIME : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _
 PERCENT DOWN : _ _ . _ _ _

PECIES CODE _ _
 PROCESSING TIME (MINUTES) _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :
 ***** LOGNORMAL DISTRIBUTION *****
 MEAN MIN. MAX. SD
 DOWN TIME : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _
 PERCENT DOWN : _ _ . _ _ _

PECIES CODE _ _
 PROCESSING TIME (MINUTES) _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :
 ***** LOGNORMAL DISTRIBUTION *****
 MEAN MIN. MAX. SD
 DOWN TIME : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _
 PERCENT DOWN : _ _ . _ _ _

PECIES CODE _ _
 PROCESSING TIME (MINUTES) _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :
 ***** LOGNORMAL DISTRIBUTION *****
 MEAN MIN. MAX. SD
 DOWN TIME : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _ : _ _ . _ _ _
 PERCENT DOWN : _ _ . _ _ _

MACHINE DATA (CHIPPER)

MACHINE NO. _ _
 MACHINE NAME _ _ _ _ _
 MACHINE CODE 19

PROCESSING TIMES AND RATES :
 TIME CODE _

SPECIES CODE _ _
 FEED RATE (FT./MIN.) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****

	MEAN	MIN.	MAX.	SD
DOWN TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :

PERCENT DOWN: _ _ . _ _ _

SPECIES CODE _ _
 FEED RATE (FT./MIN.) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****

	MEAN	MIN.	MAX.	SD
DOWN TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :

PERCENT DOWN: _ _ . _ _ _

SPECIES CODE _ _
 FEED RATE (FT./MIN.) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****

	MEAN	MIN.	MAX.	SD
DOWN TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :

PERCENT DOWN: _ _ . _ _ _

SPECIES CODE _ _
 FEED RATE (FT./MIN.) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****

	MEAN	MIN.	MAX.	SD
DOWN TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :

PERCENT DOWN: _ _ . _ _ _

SPECIES CODE _ _
 FEED RATE (FT./MIN.) : _ _ _ . _ _

PROCESSING TIME DISTRIBUTION :

***** LOGNORMAL DISTRIBUTION *****

	MEAN	MIN.	MAX.	SD
DOWN TIME :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :	_ . _ _ _ :

PERCENT DOWN: _ _ . _ _ _

MACHINE CODE 20

TIME CODE _

PROCESSING TIME (MINUTES)

DOWN TIME . . . : — . — . : — . — . : — . — . : — . — .

PERCENT DOWN : _ _ . _ _ _

PROCESSING TIME (MINUTES) _ _ _ . _ _

	MEAN	MIN.	MAX.	SD
DOWN TIME	0.000	0.000	0.000	0.000

PERCENT DOWN : _ _ . _ _ _

PROCESSING TIME (MINUTES) - - - . - -

	MEAN	MIN.	MAX.	SD
DOWN TIME	0.000	0.000	0.000	0.000

PERCENT DOWN : _ _ . _ _ _

PROCESSING TIME (MINUTES) - - - . - -

	MEAN	MIN.	MAX.	SD
DOWN TIME	0.00	0.00	0.00	0.00

PERCENT DOWN : _ _ . _ _

PROCESSING TIME (MINUTES) - - - . - - -

	MEAN	MIN.	MAX.	SD
DOWN TIME :	- - - . - - - :	- - - . - - - :	- - - . - - - :	- - - . - - - :

PERCENT DOWN : _ _ . _ _

MACHINE DATA (SPECIAL PRODUCTS)

MACHINE NO.
MACHINE NAME
MACHINE CODE 21

PROCESSING TIMES AND RATES :
TIME CODE

SPECIES CODE
PROCESSING TIME (MINUTES)

PROCESSING TIME DISTRIBUTION :
***** LOGNORMAL DISTRIBUTION *****
MEAN MIN. MAX. SD

DOWN TIME :
PERCENT DOWN :
DOWN TIME :
PERCENT DOWN :

PRODUCT DISTRIBUTION :

PRODUCT LENGTH (INCHES)	1	2	3	4	5
PERCENT	:	:	:	:	:

SPECIES CODE
PROCESSING TIME (MINUTES)

PROCESSING TIME DISTRIBUTION :
***** LOGNORMAL DISTRIBUTION *****
MEAN MIN. MAX. SD

DOWN TIME :
PERCENT DOWN :
DOWN TIME :
PERCENT DOWN :

PRODUCT DISTRIBUTION :

PRODUCT LENGTH (INCHES)	1	2	3	4	5
PERCENT	:	:	:	:	:

SPECIES CODE
PROCESSING TIME (MINUTES)

PROCESSING TIME DISTRIBUTION :
***** LOGNORMAL DISTRIBUTION *****
MEAN MIN. MAX. SD

DOWN TIME :
PERCENT DOWN :
DOWN TIME :
PERCENT DOWN :

PRODUCT DISTRIBUTION :

PRODUCT LENGTH (INCHES)	1	2	3	4	5
PERCENT	:	:	:	:	:

HEADRIG SAWING INSTRUCTIONS

HEADRIG ORDER NO.

INSTRUCTION SET NO.

SAWING PATTERN CONTROL :

SAW CODE	SP CODE	GR CODE	UPPER DIAM.	LOWER DIAM.	UPPER LGTH	LOWER LGTH	CRI. CODE	PERCENT
11	12	13	14	15	16	17	18	19
21	22	23	24	25	26	27	28	29
31	32	33	34	35	36	37	38	39

SAWING DIMENSIONS :

BOARD MIN. LGTH	HDRIG CANT	SAW KERF CANT	ROUGH CANT	BOARD THICKNESS NOMINAL	SLAB SLAR	MAXIMUM CANT WIDTH
1	2	3	4	5	6	7
11	12	13	14	15	16	17
21	22	23	24	25	26	27
31	32	33	34	35	36	37

ALLOWABLE BOARD WIDTH :

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40

ALLOWABLE CANT THICK. :

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40

HEADRIG ORDER NO.

INSTRUCTION SET NO.

SAWING PATTERN CONTROL :

SAW CODE	SP CODE	GR CODE	UPPER DIAM.	LOWER DIAM.	UPPER LGTH	LOWER LGTH	CRI. CODE	PERCENT
11	12	13	14	15	16	17	18	19
21	22	23	24	25	26	27	28	29
31	32	33	34	35	36	37	38	39

SAWING DIMENSIONS :

BOARD MIN. LGTH	HDRIG CANT	SAW KERF CANT	ROUGH CANT	BOARD THICKNESS NOMINAL	SLAB SLAR	MAXIMUM CANT WIDTH
1	2	3	4	5	6	7
11	12	13	14	15	16	17
21	22	23	24	25	26	27
31	32	33	34	35	36	37

ALLOWABLE BOARD WIDTH :

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40

ALLOWABLE CANT THICK. :

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40

CONVEYOR AND BUFFER INFORMATION

[illegible]

CRITERIA FOR ROUTING MATERIAL

[illegible]

HEADRIG SAWING INSTRUCTIONS

HEADRIG ORDER NO. 1

INSTRUCTION SET NO. - 3

SAWING PATTERN CONTROL :

SAW CODE	SP GR	UPPER DIAM.	LOWER DIAM.	UPPER LGTH	LOWER LGTH	CRI. CODE	PERCENT
1	2	17.00	16.00	24	24	2	50.0

SAWING DIMENSIONS :

BOARD MIN. LGTH	HDWIG CANT	SAW KERF CANT	BOARD THICKNESS ROUGH SLAB	NOMINAL CANT	SLAB	MAXIMUM CANT WIDTH
6.0000	0.111	0.000	1.040	1.000	1.000	1.000

ALLOWABLE BOARD WIDTH :

1	2	3	4	5	6	7	8	9	10
6.000	1.000	8.000	1.000	10.000	11.000	12.000	13.000	14.000	15.000
11	12	13	14	15	16	17	18	19	20
16.000	17.000	18.000	19.000	20.000	21.000	22.000	23.000	24.000	25.000
21	22	23	24	25	26	27	28	29	30

ALLOWABLE CANT THICK. :

1	2	3	4	5	6	7	8	9	10
7.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
11	12	13	14	15	16	17	18	19	20
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
21	22	23	24	25	26	27	28	29	30

HEADRIG ORDER NO. 1

INSTRUCTION SET NO. - 4

SAWING PATTERN CONTROL :

SAW CODE	SP GR	UPPER DIAM.	LOWER DIAM.	UPPER LGTH	LOWER LGTH	CRI. CODE	PERCENT
1	2	16.00	15.00	24	24	2	50.0

SAWING DIMENSIONS :

BOARD MIN. LGTH	HDWIG CANT	SAW KERF CANT	BOARD THICKNESS ROUGH SLAB	NOMINAL CANT	SLAB	MAXIMUM CANT WIDTH
6.0000	0.111	0.250	1.040	1.000	1.000	1.200

ALLOWABLE BOARD WIDTH :

1	2	3	4	5	6	7	8	9	10
6.000	1.000	8.000	1.000	10.000	11.000	12.000	13.000	14.000	15.000
11	12	13	14	15	16	17	18	19	20
16.000	17.000	18.000	19.000	20.000	21.000	22.000	23.000	24.000	25.000
21	22	23	24	25	26	27	28	29	30

ALLOWABLE CANT THICK. :

1	2	3	4	5	6	7	8	9	10
8.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
11	12	13	14	15	16	17	18	19	20
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
21	22	23	24	25	26	27	28	29	30

HEADRIG SAWING INSTRUCTIONS

HEADRIG ORDER NO. 1

INSTRUCTION SET NO. - 5

SAWING PATTERN CONTROL :

SAW CODE	SP GR	UPPER DIAM.	LOWER DIAM.	UPPER LGTH	LOWER LGTH	CRI CODE	PERCENT
11	12	10.000	10.000	10.000	10.000	10	10.000
12	13	11.000	11.000	11.000	11.000	11	11.000
13	14	12.000	12.000	12.000	12.000	12	12.000
14	15	13.000	13.000	13.000	13.000	13	13.000
15	16	14.000	14.000	14.000	14.000	14	14.000
16	17	15.000	15.000	15.000	15.000	15	15.000
17	18	16.000	16.000	16.000	16.000	16	16.000
18	19	17.000	17.000	17.000	17.000	17	17.000
19	20	18.000	18.000	18.000	18.000	18	18.000
20	21	19.000	19.000	19.000	19.000	19	19.000
21	22	20.000	20.000	20.000	20.000	20	20.000
22	23	21.000	21.000	21.000	21.000	21	21.000
23	24	22.000	22.000	22.000	22.000	22	22.000
24	25	23.000	23.000	23.000	23.000	23	23.000
25	26	24.000	24.000	24.000	24.000	24	24.000
26	27	25.000	25.000	25.000	25.000	25	25.000
27	28	26.000	26.000	26.000	26.000	26	26.000
28	29	27.000	27.000	27.000	27.000	27	27.000
29	30	28.000	28.000	28.000	28.000	28	28.000
30	31	29.000	29.000	29.000	29.000	29	29.000
31	32	30.000	30.000	30.000	30.000	30	30.000

SAWING DIMENSIONS :

BOARD MIN.	HDKIG	SAW KERF CANT	UPPER SLAB	LOWER CANT	ROUGH CANT	BOARD THICKNESS NOMINAL	SLAB CANT	ROUGH CANT	PERCENT	MAXIMUM CANT WIDTH
1	2	3	4	5	6	7	8	9	10	11
11	12	13	14	15	16	17	18	19	20	21
12	13	14	15	16	17	18	19	20	21	22
13	14	15	16	17	18	19	20	21	22	23
14	15	16	17	18	19	20	21	22	23	24
15	16	17	18	19	20	21	22	23	24	25
16	17	18	19	20	21	22	23	24	25	26
17	18	19	20	21	22	23	24	25	26	27
18	19	20	21	22	23	24	25	26	27	28
19	20	21	22	23	24	25	26	27	28	29
20	21	22	23	24	25	26	27	28	29	30
21	22	23	24	25	26	27	28	29	30	31
22	23	24	25	26	27	28	29	30	31	32

ALLOWABLE BOARD WIDTH :

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
12	13	14	15	16	17	18	19	20	21
13	14	15	16	17	18	19	20	21	22
14	15	16	17	18	19	20	21	22	23
15	16	17	18	19	20	21	22	23	24
16	17	18	19	20	21	22	23	24	25
17	18	19	20	21	22	23	24	25	26
18	19	20	21	22	23	24	25	26	27
19	20	21	22	23	24	25	26	27	28
20	21	22	23	24	25	26	27	28	29
21	22	23	24	25	26	27	28	29	30
22	23	24	25	26	27	28	29	30	31
23	24	25	26	27	28	29	30	31	32

ALLOWABLE CANT THICK. :

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
12	13	14	15	16	17	18	19	20	21
13	14	15	16	17	18	19	20	21	22
14	15	16	17	18	19	20	21	22	23
15	16	17	18	19	20	21	22	23	24
16	17	18	19	20	21	22	23	24	25
17	18	19	20	21	22	23	24	25	26
18	19	20	21	22	23	24	25	26	27
19	20	21	22	23	24	25	26	27	28
20	21	22	23	24	25	26	27	28	29
21	22	23	24	25	26	27	28	29	30
22	23	24	25	26	27	28	29	30	31
23	24	25	26	27	28	29	30	31	32

HEADRIG ORDER NO. 1

INSTRUCTION SET NO. - 6

SAWING PATTERN CONTROL :

SAW CODE	SP GR	UPPER DIAM.	LOWER DIAM.	UPPER LGTH	LOWER LGTH	CRI CODE	PERCENT
11	12	10.000	10.000	10.000	10.000	10	10.000
12	13	11.000	11.000	11.000	11.000	11	11.000
13	14	12.000	12.000	12.000	12.000	12	12.000
14	15	13.000	13.000	13.000	13.000	13	13.000
15	16	14.000	14.000	14.000	14.000	14	14.000
16	17	15.000	15.000	15.000	15.000	15	15.000
17	18	16.000	16.000	16.000	16.000	16	16.000
18	19	17.000	17.000	17.000	17.000	17	17.000
19	20	18.000	18.000	18.000	18.000	18	18.000
20	21	19.000	19.000	19.000	19.000	19	19.000
21	22	20.000	20.000	20.000	20.000	20	20.000
22	23	21.000	21.000	21.000	21.000	21	21.000
23	24	22.000	22.000	22.000	22.000	22	22.000
24	25	23.000	23.000	23.000	23.000	23	23.000
25	26	24.000	24.000	24.000	24.000	24	24.000
26	27	25.000	25.000	25.000	25.000	25	25.000
27	28	26.000	26.000	26.000	26.000	26	26.000
28	29	27.000	27.000	27.000	27.000	27	27.000
29	30	28.000	28.000	28.000	28.000	28	28.000
30	31	29.000	29.000	29.000	29.000	29	29.000
31	32	30.000	30.000	30.000	30.000	30	30.000

SAWING DIMENSIONS :

BOARD MIN.	HDKIG	SAW KERF CANT	UPPER SLAB	LOWER CANT	ROUGH CANT	BOARD THICKNESS NOMINAL	SLAB CANT	ROUGH CANT	PERCENT	MAXIMUM CANT WIDTH
1	2	3	4	5	6	7	8	9	10	11
11	12	13	14	15	16	17	18	19	20	21
12	13	14	15	16	17	18	19	20	21	22
13	14	15	16	17	18	19	20	21	22	23
14	15	16	17	18	19	20	21	22	23	24
15	16	17	18	19	20	21	22	23	24	25
16	17	18	19	20	21	22	23	24	25	26
17	18	19	20	21	22	23	24	25	26	27
18	19	20	21	22	23	24	25	26	27	28
19	20	21	22	23	24	25	26	27	28	29
20	21	22	23	24	25	26	27	28	29	30
21	22	23	24	25	26	27	28	29	30	31
22	23	24	25	26	27	28	29	30	31	32

ALLOWABLE BOARD WIDTH :

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
12	13	14	15	16	17	18	19	20	21
13	14	15	16	17	18	19	20	21	22
14	15	16	17	18	19	20	21	22	23
15	16	17	18	19	20	21	22	23	24
16	17	18	19	20	21	22	23	24	25
17	18	19	20	21	22	23	24	25	26
18	19	20	21	22	23	24	25	26	27
19	20	21	22	23	24	25	26	27	28
20	21	22	23	24	25	26	27	28	29
21	22	23	24	25	26	27	28	29	30
22	23	24	25	26	27	28	29	30	31
23	24	25	26	27	28	29	30	31	32

ALLOWABLE CANT THICK. :

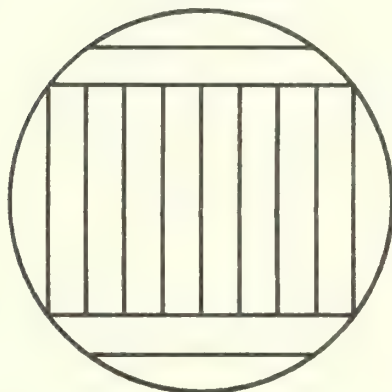
1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
12	13	14	15	16	17	18	19	20	21
13	14	15	16	17	18	19	20	21	22
14	15	16	17	18	19	20	21	22	23
15	16	17	18	19	20	21	22	23	24
16	17	18	19	20	21	22	23	24	25
17	18	19	20	21	22	23	24	25	26
18	19	20	21	22	23	24	25	26	27
19	20	21	22	23	24	25	26	27	28
20	21	22	23	24	25	26	27	28	29
21	22	23	24	25	26	27	28	29	30
22	23	24	25	26	27				

Appendix D—Available Sawing Patterns

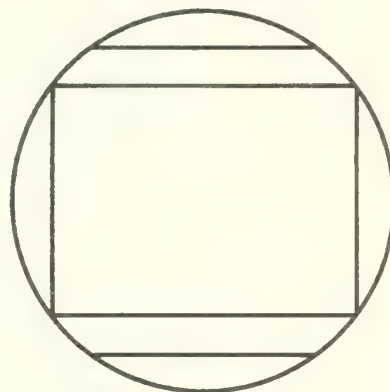
Note: The saw cuts shown in these sawing patterns are:

Headrig _____
 Cant resaw _____
 Slab resaw _____

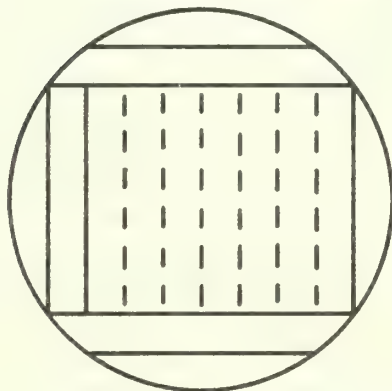
1—Saw around (all)



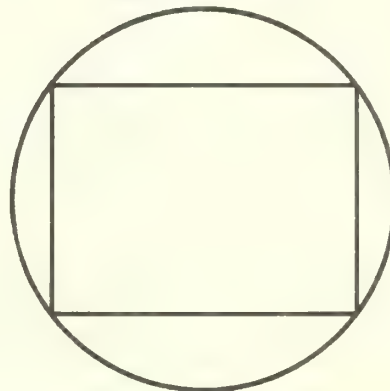
2—Saw around to timber



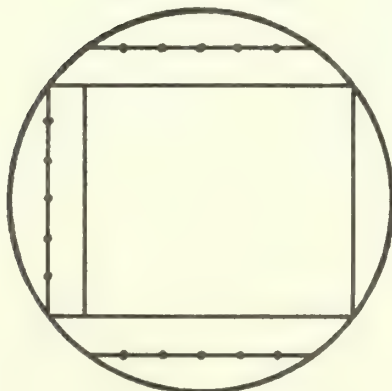
3—Saw around to cant for resaw



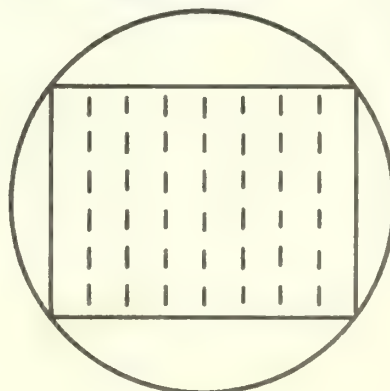
4—Slab around to timber
(slabs to chipper)



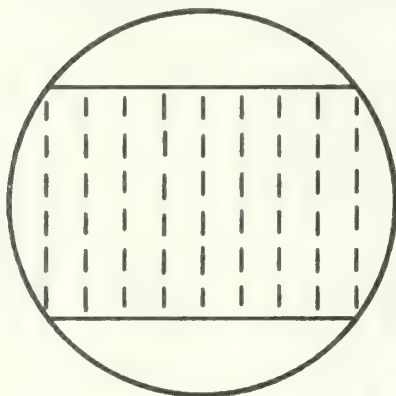
5—Slab around to timber
(slabs to resaw)



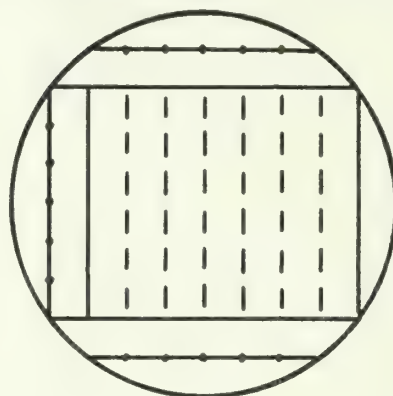
6—Slab around to cant for resaw
(slabs to chipper)



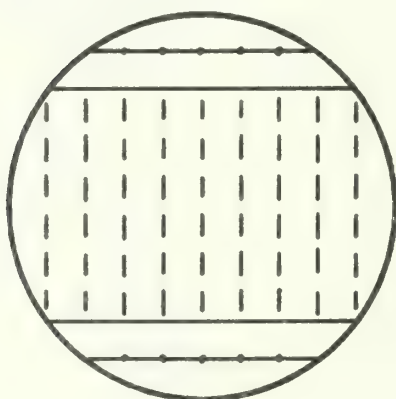
7—Slab around to 2-sided cant for resaw
(slabs to chipper)



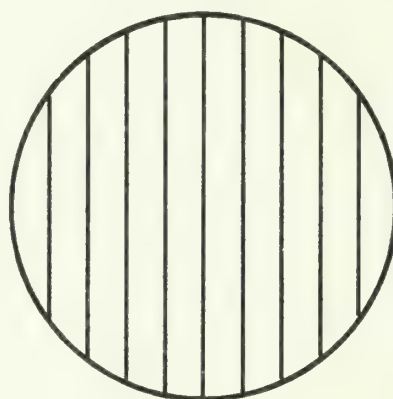
8—Slab around to cant for resaw
(slabs to resaw)



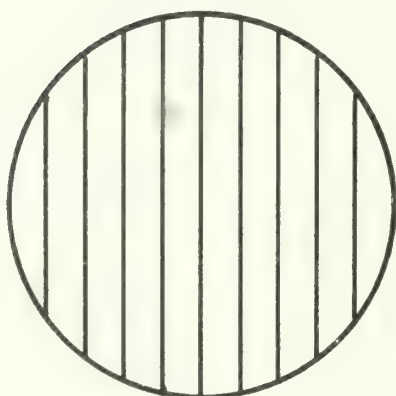
9—Slab around to 2-sided cant for resaw
(slabs to resaw)



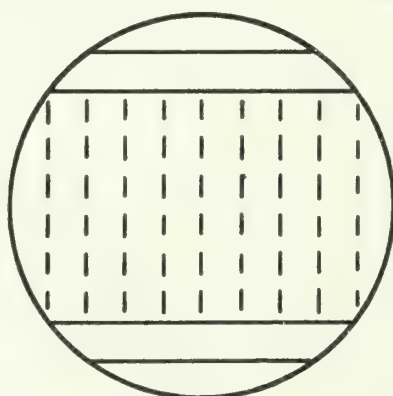
10—Live saw



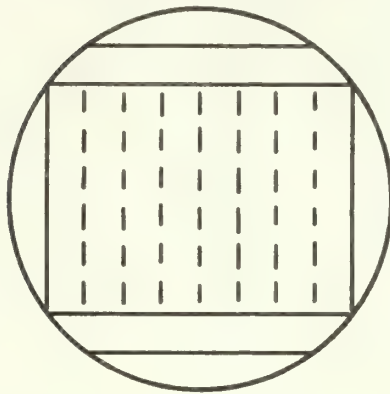
11—Gang saw



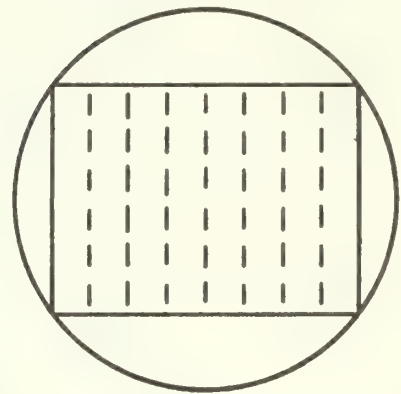
12—Saw around to 2-sided cant for resaw



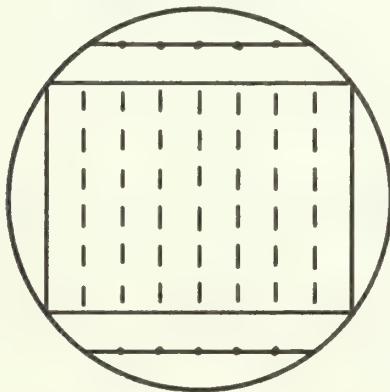
13—Same as code 3 but with even number of pieces in cant



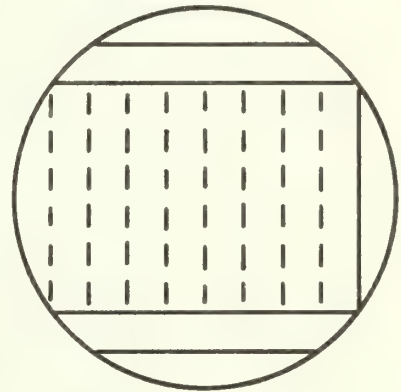
14—Same as code 6 but with even number of pieces in cant



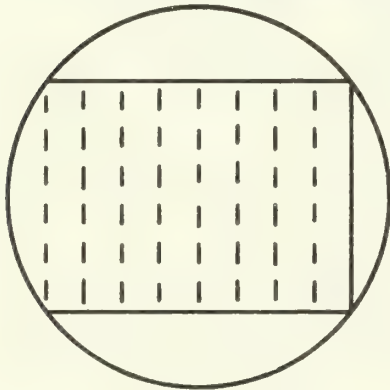
15—Same as code 8 but with even number of pieces in cant



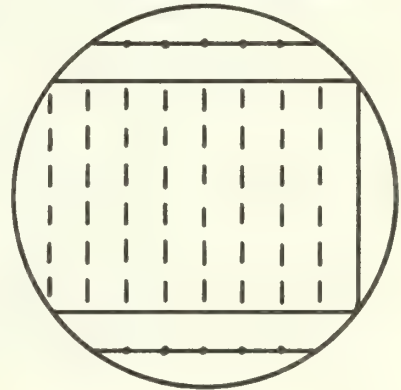
16—Saw around to 3-sided cant for resaw



17—Slab around to 3-sided cant for resaw (slabs to chipper)



18—Slab around to 3-sided cant for resaw (slabs to resaw)



Headquarters of the Northeastern Forest Experiment Station are in Broomall, Pa. Field laboratories are maintained at:

- Amherst, Massachusetts, in cooperation with the University of Massachusetts.
 - Berea, Kentucky, in cooperation with Berea College.
 - Burlington, Vermont, in cooperation with the University of Vermont.
 - Delaware, Ohio.
 - Durham, New Hampshire, in cooperation with the University of New Hampshire.
 - Hamden, Connecticut, in cooperation with Yale University.
 - Morgantown, West Virginia, in cooperation with West Virginia University, Morgantown.
 - Orono, Maine, in cooperation with the University of Maine, Orono.
 - Parsons, West Virginia.
 - Princeton, West Virginia.
 - Syracuse, New York, in cooperation with the State University of New York College of Environmental Sciences and Forestry at Syracuse University, Syracuse.
 - University Park, Pennsylvania, in cooperation with the Pennsylvania State University.
 - Warren, Pennsylvania.
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